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LIFE-SUPPORT SYSTEMS FOR INTERPLANETARY SPACECRAFT AND SPACE STATIONS OPERATING FOR A LONG PERIOD OF TIME

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LIFE-SUPPORT SYSTEMS FOR INTERPLANETARY SPACECRAFT AND SPACE STATIONS OPERATING FOR A LONG PERIOD OF TIME

B. A. Adamovich

ABSTRACT. This chapter discusses the selection and construction of life-support systems for prolonged space flights, based on regenerative physical-chemical systems. Particular methods of evaluating the reliability of these complex systems are noted. Details of a year-long sealed cabin experiment using regenerated water and oxygen are given.

INTRODUCTION

Modern advances in science and technology make it possible /3* to predict that planned conquest of the nearest planets in the solar system will begin in the near future.

Interplanetary flights and the construction of planetary stations to operate for a long period of time present space biology and medicine with a number of new and extremely complex problems. Success of the work depends, to a considerable extent, on their timely solution.

One noteworthy problem is the creation of life-support systems which are necessary to maintain the vital processes, work capacity and efficiency of the crew at a sufficiently high level [4, 6, 12, 13, 14, 15, 21, 29, 44].

* Numbers in the margin indicate the pagination in the original foreign text.

Prolonged space flights demand life-support systems which would function continuously for a period which, as a rule, exceeds the lifetime of many kinds of ground equipment, to say nothing of that required for aviation or space purposes. Therefore, the duties of the crew will include prophylactic and emergency operation of the life-support systems [10, 22, 23].

This solution, while greatly increasing the reliability of the system, at the same time imposes new limitations on it, which must be taken into consideration in solving reliability problems.

These limitations are related to human resources in completing operations specific to the spacecraft.

Another feature of the life-support systems for prolonged space flights is their uniqueness and the complexity of many elements comprising these systems. Because of this, it is /4 impossible to evaluate accurately the reliability of the system by ordinary methods.

Finally, the third feature is that, to satisfy weight and energy limitations with respect to the space vehicle, these systems must completely regenerate water and oxygen [6] and individual links in the system must be totally coordinated with the control system of the craft.

This chapter will consider complex questions on selecting and constructing life-support systems intended for prolonged (1 - 2 years) space flights, which are based on the use of regenerative physical-chemical systems.

A description of the technological regimes of individual links are given in corresponding chapters.

1. THE PURPOSE OF LIFE SUPPORT SYSTEMS

The life-support system (LSS) is one of the fundamental systems comprising the medical-biological complex supporting the spacecraft crew. It is a combination of technical or biological-technical subsystems intended to create and maintain environmental conditions in the closed area of the spacecraft which will satisfy physiological-hygienic needs as well as maintain matter-energy exchange between the crew and the environment.

The life-support system must perform the following basic functions:

1. Regenerate gases in the living compartment, maintaining its composition and pressure in accordance with medical requirements by removing from the air the carbon dioxide discharged by the crew:
   - remove poisons eliminated by the crew or the equipment in the compartment;
   - remove dust and microbic flora;
   - maintain the ion composition of the atmosphere;
   - compensate for air leaks.

2. Provide the crew with drinking water.

3. Provide the crew with food.

4. Satisfy sanitation and hygiene needs of the crew.

These functions must be performed while maintaining matter and energy exchanges of materials within safe limits (Table 1).

TABLE 1

LIST OF EXCHANGES AND CONCENTRATIONS OF MATERIALS FOR PROLONGED HUMAN EXISTENCE IN A SPACECRAFT CABIN

Food and water ration (in g/day)				Caloricity (in kcal/day
proteins	fats	carbohydrates	water	
130	120	400	2600	300

Oxygen requirement
940 g/day

Principal eliminations (in g/day)		
Water vapors	Carbon dioxide	Solid and liquid wastes
1200	1100	1880

Atmospheric conditions in the cabin			
Microclimate		Poisons (in mg/l)	
Temperature (in °C)	18	Carbon monoxide	0.002
Relative humidity	50	Amines	0.002
Carbon dioxide (in mm Hg.)	2 - 3	Ketones	0.0003
Oxygen (in mm Hg.)	160	Mercaptans	0.001
Nitrogen (in mm Hg.)	600	Aldehydes	0.0005
Pressure (in mm Hg.)	760	Alcohols	0.02

As there is a connection between exchange and the potential difference causing it, the fact must be taken into account that there must also be a potential difference between the medium

and the human organism. In the transfer of materials, the concentration of these materials in the environment acts as the medium potential. This pertains primarily to the concentration of O_2, CO_2, CO and other components of the atmosphere, as well as to the concentration of impurities in the water.

Thus one of the basic problems of the life-support system is exchanging materials $\bar{R}_0$ from the regenerator-distributor (see Figure 1) to human "discharge" and its further conversion to the "discharge" ($\bar{z}_1$ and $\bar{z}_2$) [5].

The main task of the regenerator-distributor RR here is to distribute or convert the food ration, drinking water, oxygen, sanitation-hygiene water and personal hygiene agents. /6
An accumulator stores the deficient food, oxygen, water and chemical substances (catalysts) used in operating the regenerator.

The recuperator R and the storage unit N prepare (by filtration, preliminary purification, etc.) materials for regeneration, and store non-regenerated matter exchanges $\bar{z}_3$, $\bar{R}_1$ and $\bar{R}_2$ (exhausted catalysts, by-products released in regeneration, etc.), which are periodically dumped overboard. The collector-distributor SR collects discharges (condensation of atmospheric moisture, carbon dioxide and poisons, urine, fecal matter, everyday sanitation water, microbic flora and other products) and distributes them to regenerative and non-regenerative systems.

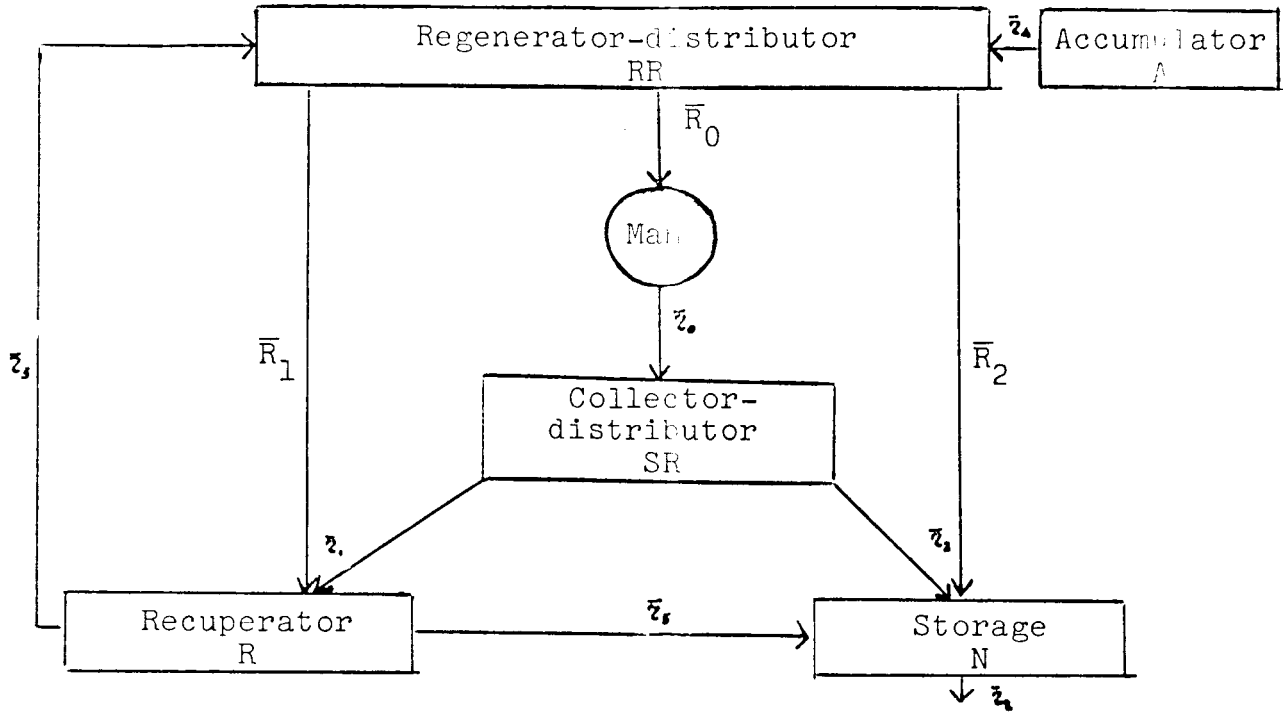

Figure 1. Block diagram of life-support system.

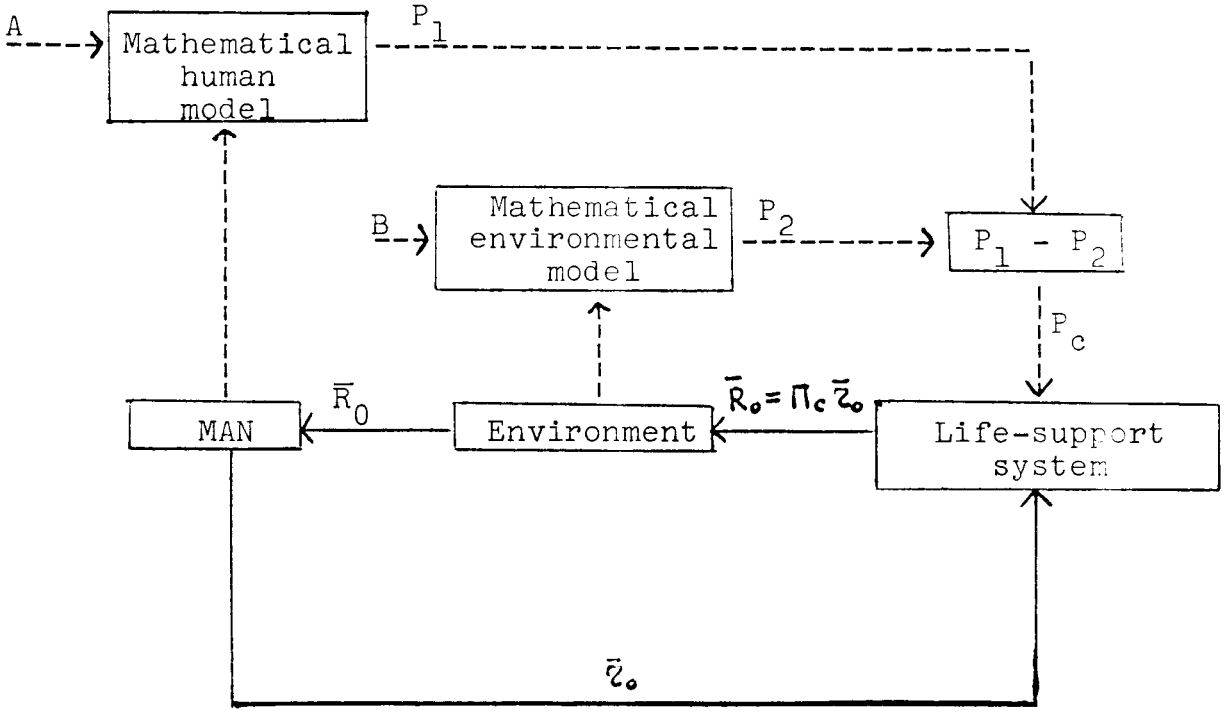

Figure 2. Diagram of material and information exchange.

Naturally such a system can be considered to be in statistical mass-exchange balance if the following conditions are observed:

$$\bar{R}_0 = \bar{Z}_1 + \bar{Z}_2 \tag{1}$$

$$\bar{Z}_1 = \bar{R}_2 + \bar{Z}_2 + \bar{Z}_3 \tag{2}$$

$$\bar{Z}_4 = \bar{R}_0 + \bar{R}_1 + \bar{R}_2 - \bar{Z}_3 \tag{3}$$

The effectiveness of mass-exchange processes will be determined by the coefficient of regeneration, which can be expressed as follows:

$$K_6 = \frac{\bar{R}_0 - \bar{Z}_4}{R_0} \tag{4}$$

From this it is evident that, when there is a complete matter cycle ($\bar{Z}_4 = 0$), the coefficient of regeneration is equal to one. When the exchange of stored matter equals the exchange in discharge to the "human" link is ($\bar{Z}_4 = \bar{R}_0$), the coefficient of regeneration is equal to zero. Table 2 gives calculations of the coefficient of regeneration as applied to several kinds of physical-chemical life-support systems. Calculations are made on the assumption that $\bar{R}_0$ = 9450 g/day and R_1 = 0. /9

The second assumption is based on the fact that the by-products produced in the regenerator — when physical-chemical regeneration processes are used — are solid wastes (carbon, mineral salts, etc.), which can only be utilized in biological-technical systems; the gaseous non-regenerated materials (methane, for example) produced in the regenerator are not regenerated under

TABLE 2

CALCULATIONS OF THE COEFFICIENT OF REGENERATION FOR VARIOUS PHYSICAL-CHEMICAL LIFE-SUPPORT SYSTEMS

No.	Type of life-support system	Consumed materials g/man-day			Coefficient of regeneration
		R_2	$\bar{Z}_3$	$\bar{Z}_4$	
1.	Reserves of liquid oxygen, food and water	0	0	9450	0
2.	Same as above + regeneration of water from urine	80	1200	8330	0.118
3.	Same as above + regeneration of water from condensation of atmospheric moisture	150	2580	7020	0.256
4.	Same as above + regeneration of everyday sanitation water	210	7970	1690	0.820
5.	Same as above + regeneration of oxygen (electrolysis of water, Sabattier reaction)	610	8960	1100	0.880
6.	Same as above + utilization of methane	580	9130	900	0.91

these conditions. An inspection of the table indicates that physical-chemical life-support systems can provide sufficiently high (to 0.91) coefficients of regeneration. Special attention /10 must be given here to the necessity of immediate regeneration of sanitation-hygiene water. Evidently, in connection with the low concentration of solids in sanitation-hygiene water, it can be regenerated with a rather high coefficient of regeneration by the sorption-catalytic methods, used in regenerating water from urine and atmospheric moisture [7]. Further development of life-support systems and the inclusion of biological links will allow non-regenerated material to be used to prepare

nutrient solutions for biological links and to increase the coefficient of regeneration. To produce a favorable environment, a number of other, no less important, factors must be considered.

For these purposes, in the development of life-support systems it is advisable to provide for material-information exchanges (basically intended to detect unfavorable factors). In the diagram (Figure 2), matter exchanges are indicated by solid lines, and information exchanges — by dotted lines.

Man is the source of material exchange $\bar{z}_o$, which enters the life-support system, is transformed there, thereby creating a favorable environment for man.

Thus, the environment is formed, on the one hand, by the life-support system, and, on the other, by man "through" the life-support system, as the conversion occurring there cannot, for example, completely remove individual differences in automicroflora or entirely eliminate all the "bouquet" of poisons excreted by man. It must be kept in mind at this point that using new, more effective energy and physical-chemical systems can also have negative aspects, which affect /11
the environment unfavorably. Thus, for example, the use of nuclear power complicates the radiation situation, increases ionization of the atmosphere and the cabin, and can lead to shifts in the isotope composition of the atmosphere. The use of new materials and new physical-chemical processes is also inevitably connected with the formation of an additional complex of poisons in the atmosphere of the cabin. All this in turn introduces new demands on the system for purifying the atmosphere of poisons and forces designers and hygienists to make intelligent compromises and find optimal solutions.

In connection with this, for the development of a conversion operator, the information-control system must have corresponding electrical human and environmental models, constructed in accordance with the level of our knowledge of A and B of these objects.

These models (normal indices) after interrogating the "human" and "environmental" links, produce the corresponding conversion operators P_1 and P_2, which enter the comparison and coordination block where the generalized operator Pe is generated. This operator provides the conversion = Pe x 0, which consequently purifies the environment. If this does not occur, the comparison and coordination block activates the emergency signal. It is impossible to eliminate completely the P_1-P_2 error, as the human model is variable. As the organism adapts to new conditions, it must be modified, i.e. it must be dynamic. In the construction of a structural and logical diagram of the comparison and coordination block, it is extremely important to establish the correlation between the parameters of the environment and the corresponding reactions of the organism to a change in these parameters. This problem can be solved more readily by conducting various human experiments under laboratory conditions simulating the environment in a spacecraft [6, 10]. /12

2. THE STRUCTURE OF THE LSS COMPLEX

The functional structure of the life-support system complex and connections between basic systems are illustrated in Figure 3.

Certain regeneration systems, depending on the purpose and feasibility of use in specific cases, can be excluded from the

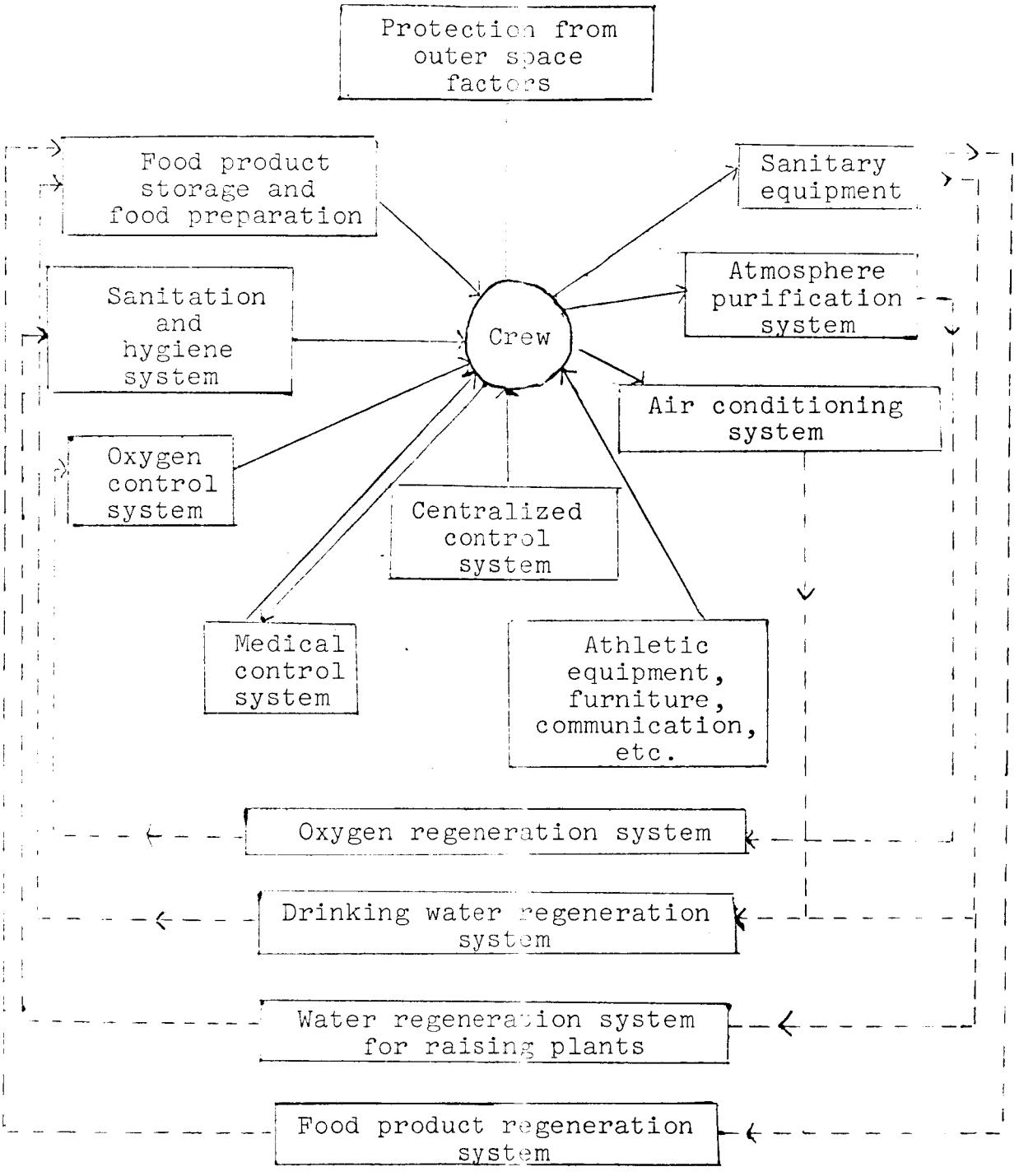

Figure 3. Functional structure of a complex of life-support systems.

complex. Therefore, their connections with other systems are shown by dotted lines.

A centralized control system must be placed over the complex of life support systems, having greater or lesser complexity and degree of centralization.

Each system can be based on various technological processes. For example:

1. The gaseous medium can be purified by CO_2 by means of sorption in various sorbent-absorbents, regenerative and non-regenerative, as well as in special membranes capable of selectively transmitting chemical compounds and materials.

2. In purifying the gaseous medium of poisons eliminated by the crew and equipment, besides the methods listed in paragraph 1, it is possible to oxidize these mixtures to CO_2 and water in special catalyzers.

3. The gas medium can be replenished with oxygen for the crew by using oxygen supplies as well as by regenerating oxygen by physical-chemical and biological methods from CO_2 and water discharged in vital human processes and by extracting oxygen from local materials on the planets. In turn, there are a large number of storage methods, from storing it in gaseous or liquid state to using supplies of various oxygen compounds, from which it can be produced by various means (water, H_2O_2, super-peroxide compounds of alkali metals, etc.). /14

4. Purifying the atmosphere of dust and microbic flora presupposes the use of various dust collectors: mechanical, electrostatic and bactericidal filters, cyclone separators, etc.

5. Biological methods can also be used to regenerate the atmosphere — for example, the cultivation of single-cell photoautotrophic organisms which absorb CO_2 and certain toxic gases and discharge oxygen into the environment.

6. The crew can be provided with drinking water both by using on-board water supplies (various methods can be used to preserve the drinking quality), and by regenerating water from moisture-containing human wastes (condensation of atmospheric moisture, urine, solid wastes) or from waste products of other spacecraft systems. Water can also be obtained from local sources on the planets.

In regenerating water, it might be feasible to use such technological processes as sorption in various absorbents, distillation at various pressure levels, filtration in selective membranes in magnetic or electrostatic fields or in an inertial-force field, oxidation of impurities in catalysts, etc. [36, 37, 38]. /15

7. The crew can be provided with food by using prepared dishes, semifinished products, or on-board food products (there are several methods of preliminary technological treatment to preserve them), as well as by regenerating food products by physical-chemical or biological methods. Regeneration of carbohydrates as components of the diet presupposes either their artificial synthesis using CO_2 and other vital products, or the use of a higher plant link with preliminary mineralization of human life products [43].

8. Several technological processes and their variants can also be used to satisfy the sanitation-hygienic needs of the crew. For example, skin can be cleansed either by washing the

hands, face and body in water using various detergents, or by drying with special hygienic napkins. There are several possible methods of regenerating linen and clothing (from washing in water and repair using needle and thread to special methods of cleaning linen and clothing and quick repairs with glue). No linen regeneration at all is also possible by sending dirty linen to the waste storage unit and taking a clean change from the on-board linen supply. Depending on the subsequent use of solid and liquid human wastes, these can be organized in various ways. If wastes are not intended for use in producing water or other substances, they must somehow be disinfected and dumped overboard or conserved and stored on board. If certain products are to be obtained from the wastes, urine must first be transported for preliminary treatment, and the solid wastes must be subjected to vacuum or thermal drying or some other treatment (including biological treatment) to obtain the necessary components. /16

The complexity of the systems and the relations between them make it difficult to make valid classifications of life-support system complexes.

One of the variables used to divide the systems into classes is the time of action (the flight): long — more than 1 year; medium — several months; and short — less than one month.

The second variable is the kind of process occurring in the system. We have in mind systems using physical-chemical processes only and those which use biological regeneration processes in addition to physical-chemical ones.

Questions on the construction of biological life-support systems based on partially or completely closed matter cycles are discussed in chapter III.

3. SELECTING A LSS COMPLEX

The choice of a life-support system variant for a specific spacecraft which will assure the combination and sequence of specific technological processes is determined by the degree to which it satisfies medical-biological, technical and organizational-economical requirements and limitations imposed with /17
respect to the crew, the spacecraft and the aims of specific space expeditions. The requirements and limitations of a life-support system with respect to the crew are determined by its needs for consumable products and, accordingly, by data on the amount and composition of discharged life products. It is also necessary to consider the ability of crew members to withstand the unfavorable effects of certain vital human products or their derivatives found in the environment and in substances consumed by the crew. Physiological-hygienic studies of these effects have resulted in limitations being placed on the content of the gaseous medium, on the maximum permissible concentrations of toxic substances in the medium, in drinking water and in water used for sanitation-hygienic purposes.

The requirements and limitations from the point of view of the spacecraft are the design and structural features of the craft, the potentialities of rocket-carriers or other means of transport and the presence of certain energy sources on board. These limitations concern spatial, design, weight and energy characteristics of the LSS.

The purposes of a specific space flight determine the number of crew members in a spacecraft, the length of time the crew spends in it, LSS reliability requirements, and the operating conditions of the spacecraft. The latter is an indirect limitation, affecting the selection of the LSS through corresponding medical-biological limitations.

The purposes of a specific space flight also determine the limitations on the operational time of a LSS for spacecraft taking part in a given expedition. The operational time of the LSS, and certain other resources which can be used in the operation, determine the organizational-economical limitations considered in selecting an LSS variant (cost, limitations on usable materials, etc). /18

Some of these limitations (such as weight, power consumption, reliability, cost, etc.) imposed on the LSS are criteria for choosing a specific variant of the system.

One of the most important criteria is the weight of the complex together with all the attendant auxiliary elements. Taken into consideration are the weight of heat and electrical energy sources, the weight of external and internal transformers and power transmitters, the weight of spare parts, tools and equipment for servicing, the weight of consumable substances, etc.

Other conditions being equal, that system is considered best which has the lowest weight criterion. This criterion can be minimized by limitations imposed on the complex by its specific use. For example, in a given craft, limited power might be assigned to life-support needs, or limitations placed

on the surface area of a radiator for discharging waste heat.

In this case, out of the large number of possible variants of a complex, that with minimal weight is chosen in which power consumption or radiator surface does not exceed given values.

It must be noted that the feasibility of finding an optimal variant for an individual system must be substantiated for each specific case.

Optimization of one system or group of systems is only /19
feasible if a change in the structure or in their technological procedures does not have a great effect on the weight of other systems in the complex. It is possible that — having economized on the weight in one system — we have more than made it up in the others.

At the present time, it is not certain that the accepted criterion is the best. Probably the criterion should include, in some form, crew efficiency, duration of the expedition, and, possibly, cost.

Lengthening flights and expeditions and the ever-increasing distance between the spacecraft and stations and the supply bases make increasingly stringent demands on the reliability and autonomy of life-support systems, on decreased consumption of material supplies and on a more closed matter cycle in the complex. Theoretical possibilities exist for developing life-support systems in this direction (see Figure 4).

/20

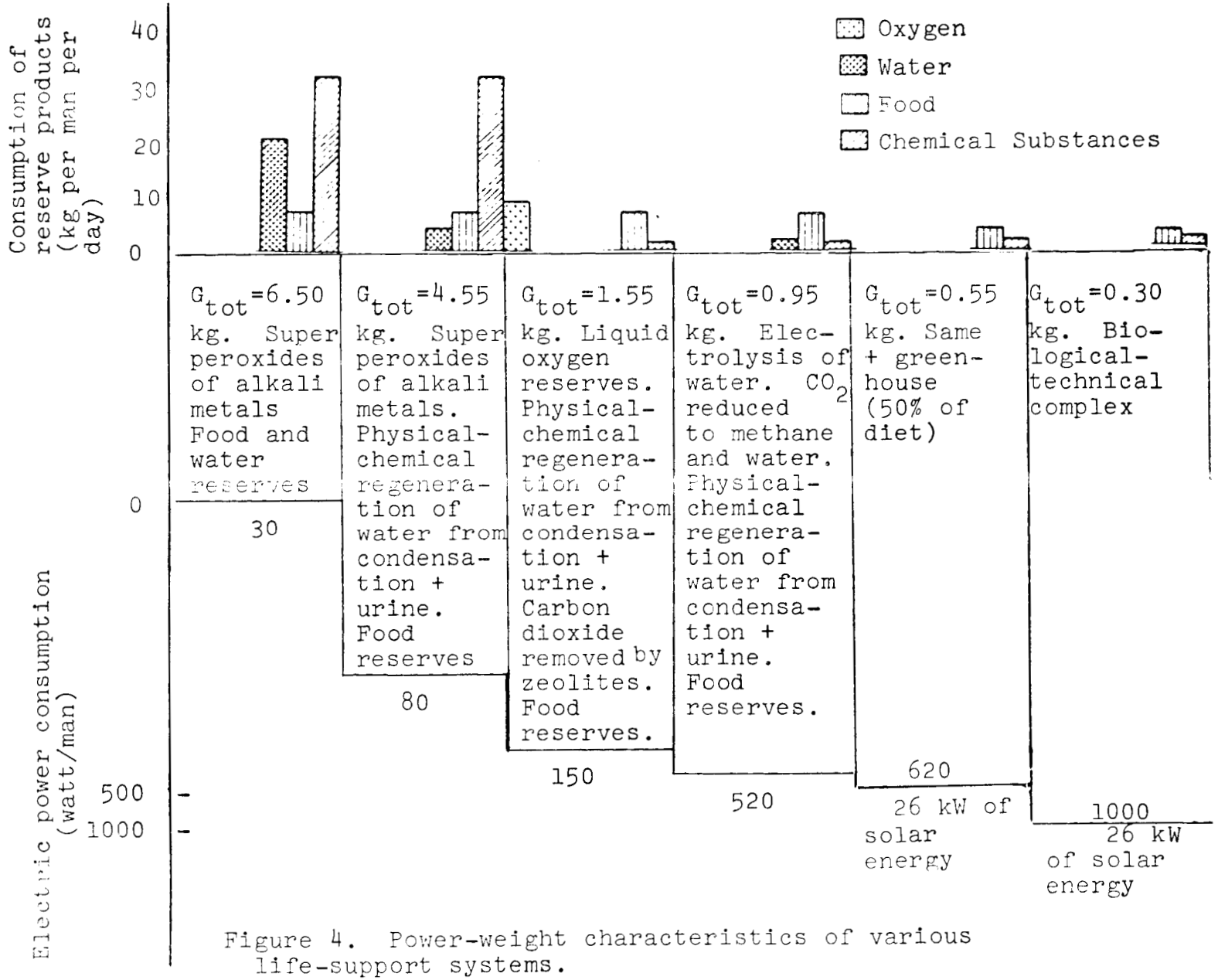
Consumption of reserve products (kg per man per day)
40
30
20
10
0
Oxygen
Water
Food
Chemical Substances
G_{tot}=6.50 kg. Super peroxides of alkali metals Food and water reserves
G_{tot}=4.55 kg. Super peroxides of alkali metals. Physical-chemical regeneration of water from condensation + urine. Food reserves
G_{tot}=1.55 kg. Liquid oxygen reserves. Physical-chemical regeneration of water from condensation + urine. Carbon dioxide removed by zeolites. Food reserves.
G_{tot}=0.95 kg. Electrolysis of water. CO_2 reduced to methane and water. Physical-chemical regeneration of water from condensation + urine. Food reserves.
G_{tot}=0.55 kg. Same + greenhouse (50% of diet)
G_{tot}=0.30 kg. Biological-technical complex
0
30
80
150
520
620
26 kW of solar energy
1000
26 kW of solar energy
Electric power consumption (watt/man)
500
1000

Figure 4. Power-weight characteristics of various life-support systems.

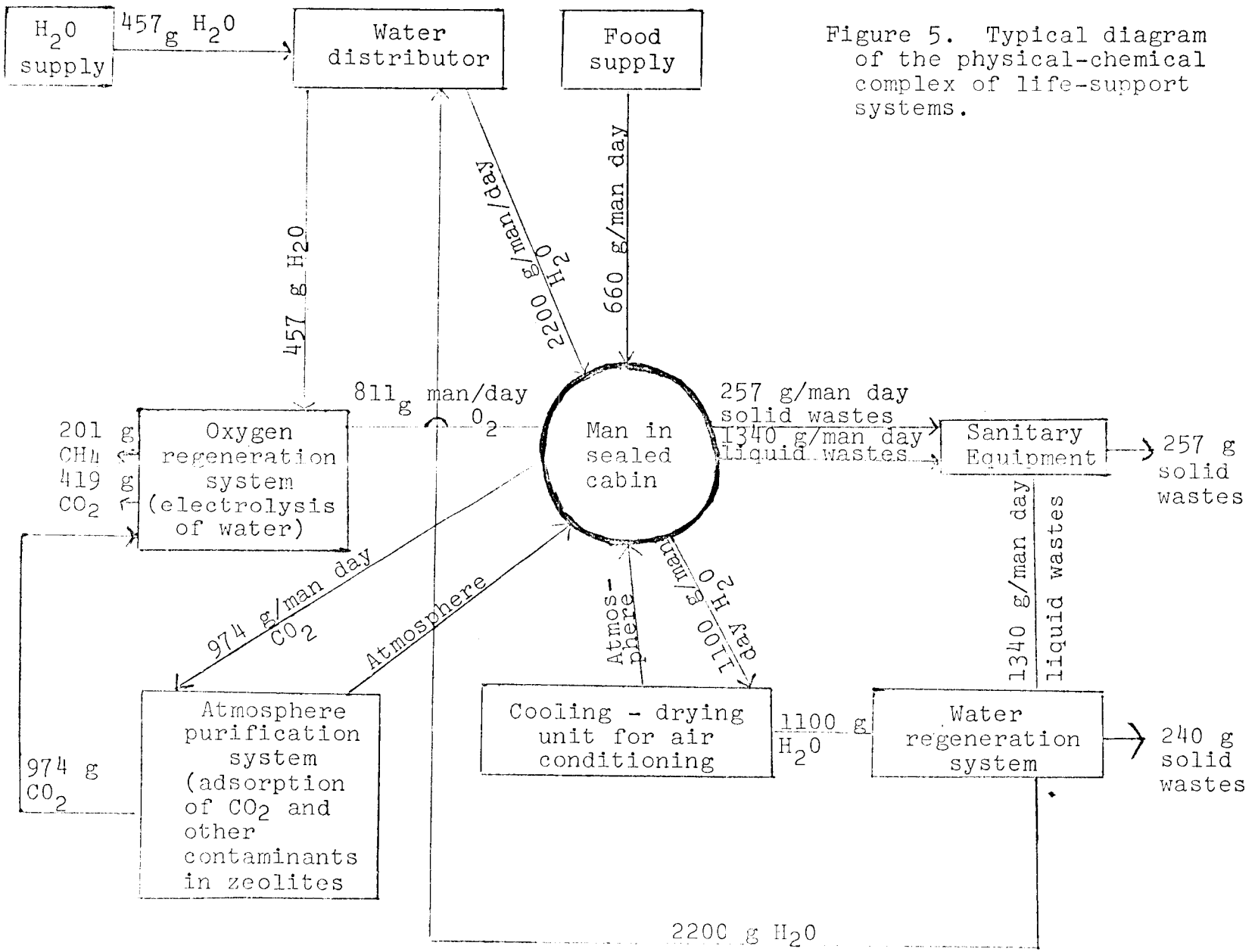

Figure 5. Typical diagram of the physical-chemical complex of life-support systems.

From Figure 4 in particular it follows that a decrease in supplies of consumable materials must be made up by an increase in the amount of energy consumed by the life-support system per time unit. /19

The concept of continuously-operating life-support systems is very broad. It takes into account the stability of their characteristics, the probability of trouble-free operation for a given length of time, time distribution of repair in case of a breakdown, and a number of other reliability criteria.

According to the above-listed criteria, the use of systems based only on physical-chemical processes is at the present time more feasible than systems which also include biological processes. /21

A typical diagram of a complex of life-support systems, based on physical-chemical processes, is given in Figure 5.

This complex, using electrolysis of water, reduction of CO_2 to methane and water, physical-chemical regeneration of water from condensation and urine as well as food product supplies, allows a supply of consumable substances per man of less than 1 kg/day.

Systems with biological links more sensitive to the effect of external flight factors are less stable in efficiency. They are heavier and their use becomes efficient only in a flight of very long duration.

Considering this, at the next stage, preference must be given to developing complexes of life-support systems which use only physical-chemical processes, and include small

biological links for purely research purposes. At the same time, studies of biological processes and the specific possibilities of using biological links in future stages of the conquest of outer space must continue.

4. ENERGY CONSUMPTION OF THE LSS

Of great importance in solving biological-technical questions in constructing life-support systems and creating a favorable environment in the spacecraft cabin are the problems and potentialities of developing cosmic power. It must be stated that the level of power development (the power potentialities of the craft) in many respects predetermines the selection of a life-support system plan and its effectiveness. For example, increasing the energy requirement per man to 200 - 250 watts makes it possible to replace a poorly effective, /22 with regard to weight, oxygen regeneration system (based on the use of oxygen-containing super-peroxide compounds) with a more refined system using the electrolytic dissociation of water and the catalytic hydrogenation of carbon dioxide [6].

Further increase in the energy capacity of the electrical power supply of the spacecraft will permit the use of an oxygen regeneration system based on complete dissociation of carbon dioxide in plasma or electrical discharge. Figure 6 gives a tentative diagram of the dependence of power consumption on expendable supply ($\bar{z}_y$). It is evident from the graph that the various types of life-support systems which maintain $\bar{z}_y$ within 0 to 10 kg per day per man can be divided into three groups. The 1st group includes life-support systems based on the use of oxygen-containing substances to provide man with oxygen and sorption-catalytic processes to regenerate water

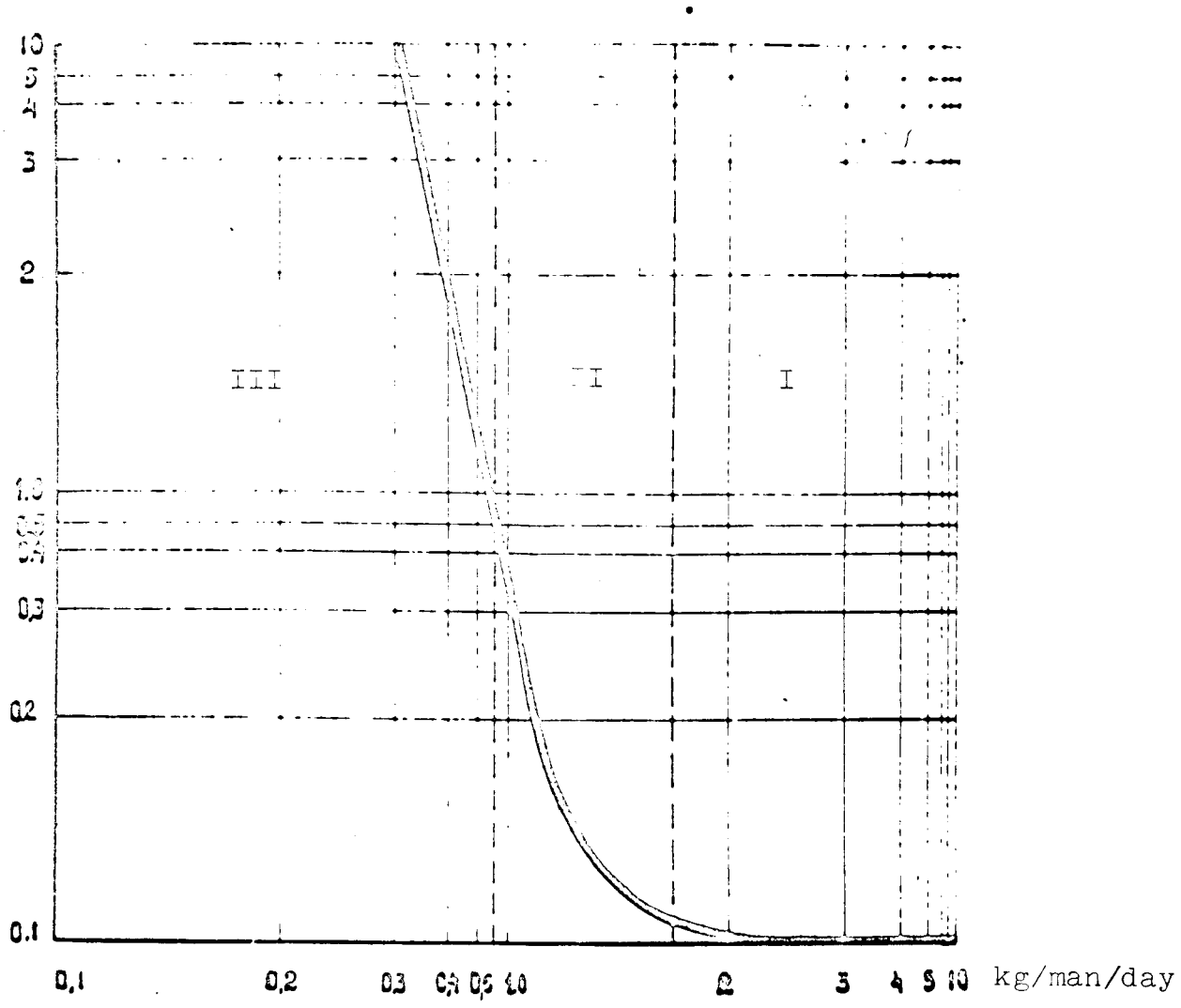

Figure 6. Tentative dependence of power consumption on expendable reserve.

from urine, condensation of atmospheric moisture and sanitation-hygiene water. This group lies within $\bar{\gamma}_y$ variations from 1.7 to 10 kg per day per man, and is characterized by energy consumption per man from 10 to 100 watts. The 2nd group includes life-support systems based on the use of oxidation-catalytic and electro-chemical processes of regenerating water from urine, regenerating oxygen, and disposing of carbon dioxide and toxic gases. This group lies within $\bar{\gamma}_y$ variations from 0.7 to 1.7 kg per day per man, and is characterized by energy consumption per man from 100 watts to 1 kilowatt.

The 3rd group includes life-support systems based on the use /24 of biological links (higher plants, algae, heterotrophic organisms, etc.) with physical-chemical correction, and in some cases duplication of biological links to provide food and to regenerate oxygen and water.

This group lies within $\bar{\gamma}_y$ variation from 0 (theoretical) to 0.7 kg per day per man and is characterized by energy consumption per man from one to 25 kilowatts. It can be assumed that biological links as a rule utilize energy from solar radiation, and in those cases when this is impossible (night and day periods on the moon, imprecise alignment of the spacecraft, etc.), they change to an autonomous power supply from nuclear electric power sources.

The absence of stringent limitations on spacecraft power makes it possible to improve the environment by using highly effective catalytic furnaces which almost completely oxidize toxic organic gases in the atmosphere of the cabin.

5. RELIABILITY OF THE LSS

The long duration of space flights and the high degree of autonomy of the LSS of spacecraft increase the difficulty of providing LSS reliability and evaluating it: preliminary (at the design stage) and final (in preflight tests) evaluation of LSS reliability.

An LSS that operates for a long time is a system that is serviced and repaired in case of breakdowns. In such a system reliability is evaluated by the probability that during operation /25 and under given working conditions a breakdown will not occur after which it would be impossible to restore working order.

Reliability of the LSS depends not only on the reliability of the technical part of the system, but also on the reliability of the crew servicing the system, on the presence of the necessary supply of expendable materials and spare parts for the system, on the degree to which the system has been studied, and on the availability of corresponding reserves of time and work in the crew in case breakdowns develop which are difficult to diagnose or which require large expenditures of time or work to repair.

LSS characteristics, including reliability, are studied at all stages of development, beginning with research in the area of technological processes which can be used in the LSS, and ending with preflight tests of the LSS, with the participation of the crew in a complete flight program. This research includes prolonged comprehensive experiments at the scientific research-development stage of the LSS, with the participation of the researchers.

In experiments of this type studies are made of the various aspects of the interaction of the subsystems and the LSS units, between themselves and with the crew. The most important medical-biological and scientific-technical problems are revealed, which demand solutions or further broader studies to successfully create a life-support system which will meet the high requirements imposed on it.

In studying LSS reliability, three types of catastrophic breakdowns can be imagined. /26

The first type occurs if, during the expedition, it is discovered that the supply of the consumable substances in the system is exhausted, and reserve resources of the system and the human organism will not last until the end of the flight.

This type of catastrophic failure can be described using symbols of formal logic.

$$\bigvee_{i=1,\dots n}\left\{(g_i \tau_{op} > G_{stor\,i}) \wedge [(\tau_{op} - \tau_{gi}) > \tau_{res.gi}]\right\} \qquad (5)$$

Here g_i — the average daily consumption of substance i (kg/day);

$G_{stor \cdot i}$ — the amount of substance i stored on board (kg)

τ_{op} — operating time of the life-support system (days);

τ_{gi} — time, in the course of which all substance i would be consumed (days);

$\tau_{res \cdot gi}$ — total reserve operating time of the system and the human organism without substance i (days).

Here and below it is assumed that outside help for the crew or premature return to earth is impossible, which is

valid with respect to interplanetary spacecraft and stations, and more or less valid at the present time with respect to lunar stations. If necessary, however, this factor can also be computed by replacing τ_{op} with τ_r, where τ_r is the time from the beginning of the expedition to the arrival of help or return to earth.

The second type of catastrophic failure could occur if the supply of reserve elements, even of only one kind, on board will not last for a given operating time and the resources of the system and the human organism will not enable man to survive until the end of the flight. /27

Formally this can be described:

$$\bigvee_{j=1,\ldots,m} \left\{\left(\frac{\tau_{op}}{\tau_{pj}} > n_j\right) \wedge \left[(\tau_{op} - \tau_j) > \tau_{res\,j}\right]\right\} \qquad (6)$$

Here τ_{pj} — resource of type-j element (days)

n_j — number of type-j elements stored on board (including reserves and operating elements) (pieces);

τ_j — time during which the entire reserve supply of type-j elements would be consumed (days);

$\tau_{res \cdot j}$ — total reserve time of the system and the human organism under the effect of those factors which will occur when the last type-j element fails, and there is nothing with which to replace it (when it is impossible to repair it on board)(days).

The third type of catastrophic failure occurs when the time is longer than the total reserve time of the system and of the

human body according to the most intensive factor — the result of this failure

$$\bigvee_{\kappa=1,\dots,s}\left[\left(\sum_{l=1}^{l=u}\frac{T_l}{\alpha_l z_l}\right)_\kappa > \min\left(\tau_{\text{res},\kappa}\right)\right] \qquad (7)$$

Here recovery time is considered to be the total time of successively-performed recovery operations (for example: making a technical diagnosis, locating the broken element, replacing the element, adjusting the system after repair, starting up the system or unit, etc.).

The time of each operation is evaluated by the term $\frac{T_l}{\alpha_l z_l}$, where

T_l — the time consumed in operation-l in man-hours; /28

z_l — the number of crew members involved in operation l;

α_l — coefficient of change in the efficiency of a crew member in performing operation l;

s — the number of failures in the system during the entire operating time.

u — the number of operations in restoring the system after the failure.

If the probability of the first type of catastrophic failure is designated as P_1, the second type as P_2 and the third as P_3, the total probability of catastrophic failure is as follows. It will be equal to the sum of probabilities of all three types of catastrophic failures

$$P_{\text{cat.}} = P_I + P_2 + P_3 - P_IP_2 - P_2P_3 - P_IP_3 + P_IP_2P_3, \qquad (8)$$

and the probability that during the expedition no catastrophic failures will occur in the system, i.e. the reliability of

the system - H can be written as the product of the difference between one and the corresponding probability

$$H = (I - P_1)(I - P_2)(I - P_3) \qquad (9)$$

Now we shall consider what determines the probability of catastrophic failure.

The probability of catastrophic failure depends:

— on our uncertain knowledge about the performance and working conditions of the system under consideration, about defects in its materials, about loads on the system, about changes in the properties of materials with time, etc.;

— on the inadequacy of so-called "safety factors" chosen in each design cross section of the system, including the case when the system is not considered in certain kinds of loads or is disregarded in calculating certain factors affecting reliability. /29

The above can relate not only to the life-support system proper, but to the crew as well. The crew works in a certain regime and under certain conditions. It has a certain capacity with regard to solving any problems, which can be altered by conditions and time. It has certain internal defects both within crew members and in their interactions with each other, and we have no generally accurate data about any of these.

None of the values in expressions (5), (6) and (7) are strictly determined, but they have probability characteristics,

as they depend on a great many other (including random) variables. Some of these variables we know how to allow for (they also are not determined). We know only that some of the others exist, but cannot say anything definite about them; about others — we are not even sure they exist.

Let us examine several of the parameters in expressions (5), (6) and (7).

I. Average daily consumption g_i of substance i depends on:

— the matter balance of the crew, which depends on energy consumption and certain conditions in a sealed space;

— the effectiveness of using this substance in the life-support system;

— possible losses of the substance.

II. The operating time of the system (in a given flight trajectory) depends on navigational errors, which in turn depend on errors in measurements:

— linear and angular coordinates of the spacecraft; /30

— time

— speed of the spacecraft;

— thrust;

— direction of thrust, etc.

It is very possible that the probability that some of these errors will occur is dependent on the efficiency of crew members.

III. The total reserve time of the system and the human organism, based on a deficiency of substance i, depends on conditions in which man lived and worked before this substance was exhausted, on the work load to which he will be subjected in the subsequent period, and on individual human characteristics, etc.

IV. Resources of element-j of the system depend on conditions under which the element operates and on its load — not only static, but also dynamic.

V. The time consumed in a certain operation in restoring the system to working order depends not only on the complexity of the work itself, the accuracy and precision necessary to perform it, but also on the complexity of inter-system relations, on the number of damages or failures immediately following the first breakdown, on the completeness of the control system, and on the availability of substitute elements, etc.

VI. The number of crew members involved in repairing the life-support system after K failures depends not only on the number of people necessary to perform a given duty, but also on:

— the probability that, in repairing the system after the K-failure, K + 1 failure will not occur, requiring urgent measures;

— the living schedule of the crew; /31

— the crew's work load with other duties;

— probable efficiency losses because of sickness on board, etc.

VII. Finally, the coefficient of change in efficiency α, which depends on a number of factors.

Any of the values in the expressions characterizing a certain type of catastrophic failure depend, in turn, on other variables. For example, the average daily consumption of a certain supply substance is determined by the "net" requirements of all elements of the system (including the crew) using the substance, the performance of all elements of the system regenerating it, the effectiveness of using the substance, its losses during use and regeneration, etc.

If a specific substance, for example, water, is considered, the relations between average daily consumption of this substance and other indices become more specific.

It can be assumed that water in a certain spacecraft is used for drinking and preparing food, for washing and cleansing the body — for producing oxygen necessary for breathing.

In this craft, consumable water is regenerated from moisture-containing human wastes, from contaminated sanitation water, and by using carbon dioxide discharged by the crew and hydrogen remaining after producing oxygen from water.

The average daily consumption of water from supplies on board the craft will depend:

— on the water ration of the cosmonauts, which is determined by the diet, by the distribution of energy expenditure in time, by pressure and composition of the atmosphere, its temperature and moisture content, etc;

— on water losses by evaporation or other ways in food preparation; /32

— on how well the technological process of washing and body cleansing is organized and how effectively detergents are used;

— on the amount and composition of skin excretions of the crew, which depend on their diet, energy expenditure, microclimate conditions;

— on the oxygen ration of the cosmonauts, determined by energy expenditure and diet;

— finally, on the degree of water regeneration in the system, which is determined by the refinement of the technological processes used.

Change in cosmonaut efficiency is also determined by the condition of the organism, which depends on the length of time the individual spends in the spacecraft, on living conditions, and on individual characteristics of the organism;

— and relations between crew members;

— and their work load;

— and the training required to perform specific tasks;

— and conditions in the spacecraft during the emergency period;

— and, finally, the importance which the cosmonauts attach to performing a given task.

We see here that a number of indices are included in one complex which should appear as the result of physiological-hygiene, psychological, technical and organizational studies.

The resource of a certain element in the system depends on the conditions under which it operates, on its load, on the training of the crew to service the system, as well as on how correctly the above-noted indices were evaluated in the development of this element. /33

A brief survey of a few relations between certain important parameters, from the point of view of advances in the reliability of life-support systems, indicates:

— that studies of many relations, similar to those noted, between parameters are extremely time consuming if they are made of individual subsystems or elements;

— that some important relations appear and can be studied only during the interaction of all elements of the system between themselves and with the crew.

Especially important is the case when we do not know exactly which factors (for example, microcontaminants which we have not yet identified) might have an important effect in prolonged operation.

It follows:

— that for conducting a number of studies of the interaction of subsystems and elements of the life-support system, between themselves and with the crew, comprehensive experiments are not interchangeable. In solving other reliability problems of the life-support system, time is gained by comprehensive experiments, as — in experimenting under conditions close to actual ones — direct measurements and statistical analysis can be made not only of data on failures of particular elements, but also on data of actual conditions and performance of elements, on servicing and repairing the system, and a number of other characteristics. Comprehensive experiments also develop the most /34
economical methods of servicing and repairing equipment, its placement requirements in spacecraft quarters, and the algorithm of finding failures. They make it possible to accumulate statistical data for creating a technical diagnosis system, etc.

6. MASS EXCHANGE IN THE LSS

A regenerative life-support system is a complex of interconnected biological and physical-chemical processes, forming a partially closed-matter cycle. The degree to which it is closed serves as the basic qualitative index of the LSS. This index is, on the one hand, a function of mass-exchange characteristics of the system and the elements comprising it. On the other hand, it depends on technical accomplishment, taking into account superimposed limitations (weight, dimensions, power expenditure, reliability and others). The main stipulation of the work of the LSS is to satisfy given requirements for living conditions of the crew. Therefore, constructing such systems is a many-sided task, which is unusually complicated theoretically and experimentally. This problem can be satisfactorily solved only

by coordinated efforts in experimental research (test evaluations of the LSS), by more extensive theoretical knowledge in medicine, biology and technology, as well as by developing mathematical methods of studying processes in the system. The new field of knowledge — space biology and medicine — confirms the necessity of such coordinated studies.

For multi-level research, such as the development of an LSS, /35 the basic approach to solving the problem must first be determined. Without claiming any final solution to this question, we can offer the following concept:

— the basic connective factor in LSS research is studying the mass-exchange characteristics of processes which connect elements of the LSS to the complete system;

— these mass-exchange characteristics must, first of all, satisfy the requirement of providing living conditions for the crew. Therefore, the different levels of research combine the common limitations or criteria taking this requirement into account;

— a theoretical study of mass-exchange characteristics necessitates the development of specific methods of mathematical description for formalized computation of various factors, for analysis and optimization of the systems;

— mass-exchange characteristics used in theoretical study must be based on reliable experimental data;

— to obtain reference data for LSS development, it is necessary to make comprehensive experiments, where processes occur for a sufficiently long period of time under conditions

which are maximally close to planned flights.

It is advisable, in theoretical studies of mass-exchange processes in the LSS, to concentrate attention primarily in two directions.

The first direction is related to developing a theory of LSS construction, the evaluation of its quality and the selection of system control algorithms as a whole. This is extremely important, because the results of analyzing different LSS variants make it possible to reduce material expenditures in the development of unpromising variants. The practical outcome of system construction theory would be programming the optimal development sequence of various types of LSS for space exploration. /36

Only the first steps have been taken in this direction. A theoretical study of LSS processes has been attempted from the aspect of mathematical programming. The theory is based on the assumption that matter-conversion processes in individual elements of the system (its link) can with sufficient practical accuracy be considered stationary and linear, with reference to the accepted coordinates — material (for matter flow) and power (for energy flow) consumption. The functioning of each of the links can be described by the equation:

$$y_{out}^{(j)} = y_{in}^{(j)} B_j, \qquad (10)$$

where $y_{in}^{(j)}$ — vector-line, the input* from link j,

$y_{out}^{(j)}$ — vector-line, the output from link j,

B_j — matrix, reflecting matter converions (energy in the link).

*Translator's Note: The foreign text mistakenly gives output here.

If conversion links exist, and if coordinates are considered, the set of equations describing the work of the LSS takes the form (see Figure 7):

$$X_{out} = X_{in} \sum_{j=1}^{m} A_j B_j C_j \qquad (11)$$

$$X_{out} \cdot f^T = X_{in} \cdot f^T \qquad (12)$$

where X_{in}, X_{out} — 2n-dimensional vector-lines, /38

A_j, B_j, C_j — 2n x n, n x n, n x 2n-matrices, respectively,

f = (in, On) — 2n-dimensional vector-line,

in and On — n-dimensional lines. The first has all elements equal to one; the second — to zero,

T — symbol of transposition.

The equations for describing "internal" limitations are determined. For example, the requirement for given living conditions for the crew (defined by the vector y^0_{man}) is expressed by the equation:

$$X_{in} \cdot A_1 = y^0_{man} \qquad (13)$$

On the basis of the mathematical model developed, methods have been chosen for solving two basic problems: the first subproblem consists of coordinating matter and energy flows in the system, with allowance for "internal" limitations (requirements for living conditions, permissible changes in parameters of the links, etc.). The second subproblem lies in optimizing the system, taking into account "external" limitations (mass of the system, its energy consumption, etc.).

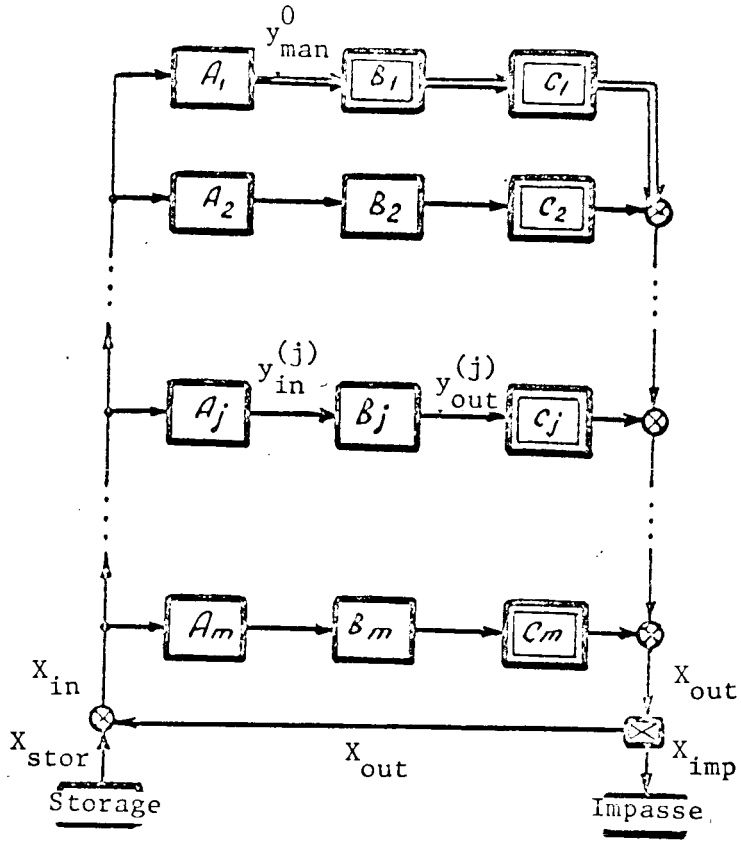

Figure 7. Block diagram of mass-exchange processes in the LSS.

Within the tolerance limits accepted in developing the mathematical model, when linearity of matter conversion is assumed, the system of internal limitations is expressed as a set of linear equations. Consequently, the first subproblem is one of linear programming. The second subproblem, in the usual case when the criterion (mass of LSS or "reduced" mass) depends nonlinearly on the coordinates and parameters of the LSS, becomes one of nonlinear programming.

Practical calculations using this theoretical approach are related to the necessity of knowing the generalized parameters of matter conversion in links Cj and some of links Bj (j = 1, 2, ..., m_1) as well as the range of permissible changes in elements of matrix $B_{m_1} + 1, \ldots, B_m$. In optimal synthesis of the LSS, matrices Aj and $B_{m_1} + 1 \ldots, B_m$ are determined. For initial calculations, the necessary values were obtained on the basis of existing literature data (accumulated information on human physiology and biological elements in the life-support system; data on physical-chemical processes in other links of the life-support system). However, experimentation is necessary to more accurately define the parameter values and to verify the accepted assumptions about processes in the LSS. Data accumulated during a year-long medical-technical experiment were also used here. /39

The second direction of theoretical research consists of calculating certain contours of the life-support system in which the processes are not connected (or weakly connected) with processes in the rest of the LSS.

The practical value of this kind of research is that in a greatly simplified model data can be obtained which are valuable for LSS development: optimization of separate contours and selection of their control algorithms. This is especially important in cases when the selected contour, in conformity with a specific flight, performs an independent function, i.e., it is autonomous.

To illustrate this direction of research, we shall discuss the contour of regulating the concentration of carbon dioxide in a sealed cabin. The concentration is maintained by a physical-chemical atmosphere purification system (APS) in the LSS which /40

uses regenerative sorbents (Figure 8). The mathematical description of this contour is very simplified. It is based on a number of assumptions, the most important of which are:

(1) it is assumed that the contour is independent of processes in the rest of the LSS;

(2) the linearity of the adsorption process with respect to a moving gradient;

(3) sorption occurs under isothermal conditions;

(4) the initial conditions after completion of the desorption process depend only on the conditions at the end of the sorption process;

It has the form:

Equation of sealed cabin, following from matter balance

$$\frac{V}{RKT}\frac{dc(0,t)}{dt}+\frac{G}{RT}c(0,t)=G\cdot c(L,t)+\frac{g(t)}{RT}; \quad (14)$$

The system of equations describing the process in the adsorbent [3], [4]:

$$\frac{\partial \omega(x,t)}{\partial t}=\beta[c-f(\omega)]_{[\text{for } (k-1)t_u<t\leq kt_u]} \quad (15)$$

$$-\frac{\partial c(x,t)}{\partial x}=\frac{\beta}{G}[c-f(\omega)] \quad (16)$$

Initial conditions of the adsorption process:

$$\omega(x,0)=\bar{\omega}_0(x)$$
$$\omega(x,k,t_u)=\omega_0[x,(k-1)t_u \quad (17)$$

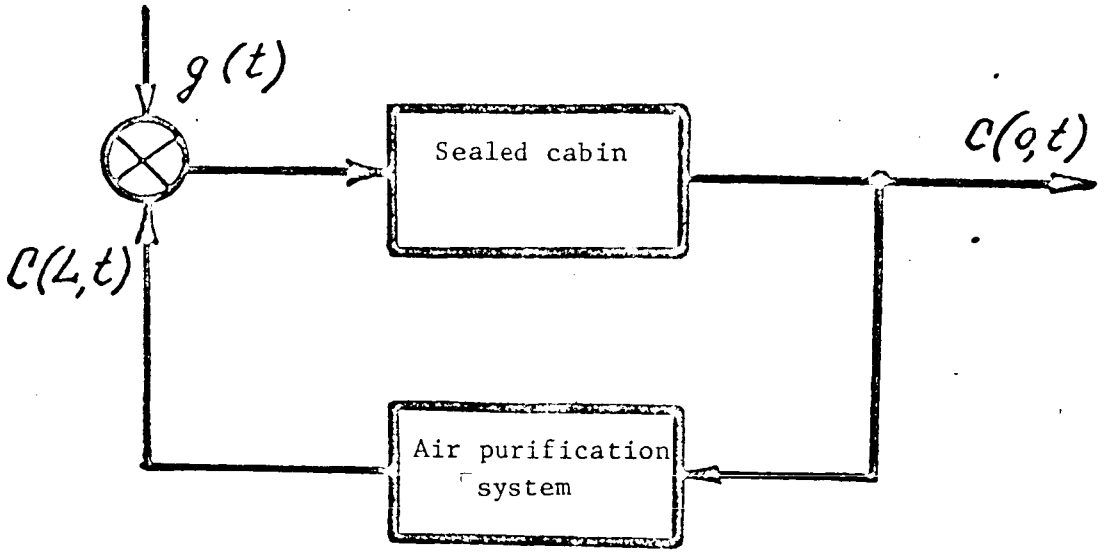

Figure 8. Block diagram of the contour of regulating CO_2 concentration in a sealed cabin.

The boundary conditions C(O, t) are determined by solving the equation of the sealed cabin:

where V — volume of the sealed cabin;

T — absolute temperature;

P — total pressure;

R — gas constant; /42

G — expenditure of air through the APS;

C and ω — concentration of carbon dioxide in the air and in the sorbent, respectively;

g(t) — rate of carbon dioxide discharge by the crew;

L — length of cartridge,

f(c) — function, determined on the basis of the adsorption isotherm;

t and X — running time and length;

β — coefficient of mass transfer;

a and b — constants determined by technological parameters of APS and the gas mixture in the sealed cabin;

tn — operating cycle time of APS cartridges (k = 1, 2, ... -number of cycle).

The criterion for optimizing this contour could include the mass of the atmosphere purification system (M), its energy consumption (E) and requirements for carbon dioxide concentration in the sealed cabin /C(o,t)/:

$$\min F[C(0,t), ME] \qquad (18)$$

Let us turn our attention to four elements of this mathematical description: parameter and functions f(c), ω and g(t). The rate of carbon dioxide discharge by the crew — g(t) — can for preliminary calculations be determined on the basis of existing data on human physiology (the graph of energy-expenditure changes is determined by the known work activity regime, and function g(t) is calculated according to this regime with a specific diet). The accuracy of the calculation can be proved, and function g can be defined more accurately only on the basis of experimentation. Parameter β and functions ω_0 and f can be determined in the course of studying the materials and construction in APS development. /43 These elements of the mathematical description are verified, in the same way as the accepted assumptions are, during the course of independent (stand) APS tests, in which human dummies can be used to realize function g(t). But all these measures in no way exclude the necessity of conducting comprehensive experiments with the participation of man, during which the mutual effect of component parts of the LSS on each other can be revealed (in particular, the effect of microcontaminants in the atmosphere or duration of the expedition on the parameters of APS sorption materials). Only prolonged comprehensive experimentation can establish the accuracy of the contour

mathematical models and the accuracy of the accepted simplified assumptions.

A special role in experimental research is played by obtaining and refining data on the intensity of mass-exchange processes in the human organism. In coordinated theoretic and experimental research directed toward LSS development, only data on average quantitative characteristics (obtained by averaging by unit or by time) are inadequate. Data are needed on the dynamics of mass-exchange processes (change in quantitative characteristics with time), as well as statistical parameters of random deviations caused by instability or individual variations in crew members.

This information is very important, because data from one experiment can be used to analyze a number of LSS if it is assumed that no marked changes will be observed in living conditions during their operation which could affect human mass-exchange processes. /44

Information on mass-exchange processes in the human organism can be obtained in various ways. In general use at the present time are physiological studies conducted by specially developed methods which provide for medical examinations and observations, and a set of tests and physiological probes. All these measures are carried out discretely at certain moments of time.

Another possibility for studying quantitative features of mass-exchange processes is using life-support system complexes. This plan consists of continuous observation of changes, in time, in the environmental medium around the crew. Necessary characteristics are obtained after mathematical analysis of data on changes in the parameters of the environment.

The second method has certain advantages, including "passive" methods of collecting data, when nothing constrains the naturalness of the crew; continuous observations; no information loss, as changes in the medium are generally established by automatic instrumentation. But there are also disadvantages in this method, the most important of which is less accuracy, which is related to the indirect method of measurements.

During the year-long medical-technical experiment described below, extensive material was collected on physiological studies and a large volume of information on measuring the environmental medium. As a result of the accumulated information, it was revealed that data on changes in the parameters of the environmental medium will greatly expand physiological research methods.

7. COMPREHENSIVE GROUND TESTS OF THE LSS

The reaction of man to the prolonged effect of a combination /45
of environmental factors, the compatibility of the systems with each other and with man, the reliability of the systems, their control, the organization of crew activity in the expedition, and other important problems can be solved and worked out only by using long-term experiments.

In this connection, the basic problems in creating life-support systems characterized by high regeneration coefficients can be solved and worked out by using ground experiments.

This is what K. E. Tsiolkovskiy had in mind when he wrote that, "It is entirely possible in practice to develop and test on earth means of human respiration and nutrition in isolation" [40, 41, 42, 43].

A special technical base is needed to conduct these experiments which will allow complex life-support systems having different purposes and structure to be tested with human participants, under conditions on the Earth.

While preliminary design analysis helps determine which variants of life-support system complexes should undergo experimental testing and which technological processes are most promising for investment, a prolonged ground experiment enables us to study in practice the interactions of systems and to obtain data which define more accurately a number of important characteristics of the complexes. It aids in planning the construction of more effective life-support systems for use in space and in solving the more complex problems facing modern astronauts [2, 4, 6]. /46

To solve these problems, a ground complex of promising life-support systems has been created, based on the latest Soviet achievements in biology, technology, chemistry and medicine and equipped with modern research and monitoring equipment. Included in this complex are intricate physical-chemical and biological-technical systems for regenerating water from urine and condensed atmospheric moisture, regenerating oxygen from water, regenerating daily sanitation water, purifying the atmosphere of carbon dioxide and toxic gases, with the use of regenerative absorbents, the utilization of carbon dioxide, growth of vitamin-rich plants, etc. [10, 11].

On 5 November 1967, a year-long medical-technical experiment was begun in this life-support system complex. Participating in the test were three researchers: Doctor G. A. Manovtsev (leader of the group), biologist A. N. Bozhko, and technician B. N. Ulybyshev.

The experimental program studied the following basic problems:

— establishing the feasibility of prolonged (up to one year) human existence and of maintaining adequate efficiency in isolation in a sealed chamber of limited dimensions with water and oxygen requirements regenerated from human wastes, using almost completely dehydrated food products;

— studying the mutual effect of the systems and man, the changes in the environment under these conditions, and verifying /47
accepted methods of medical control and research to obtain reference data for developing a complex of medical-biological measures to support crews in space vehicles for long flights;

— studying and working out technological regimes and constructions of individual units to obtain basic reference data for reasonable projection of life-support systems with more complete regeneration of water and oxygen from human wastes.

To obtain the most complete information on the mutual effect of individual systems on man and on other systems, the year-long experiment, according to the program, was conducted in three stages. These provided for sequential connection of life-support systems to the complex. At the first stage of the experiment (November 1967 - February 1968) it was possible to give basic consideration to the problem of providing water; in the second stage (January 1968 - April 1968) the effectiveness of the experimental greenhouse was studied; and in the third stage (May 1968 - November 1968) the problem of providing oxygen was considered.

The ground complex of life-support systems included systems providing the greatest possible regeneration of oxygen and water, as well as auxiliary and duplicate systems.

The interaction of these systems in the complex makes a partially closed matter cycle possible. A schematic diagram of such a system is given in Figure 9.

This diagram shows experimental values of material matter flows in g/day for three persons. These values were obtained during the third stage of the experiment.

In the year-long experiment, a specially developed diet was /49
fed the researchers. It consisted of vacuum dried dehydrated products, containing an average of 117 g of fats and 361 g of carbohydrates. The basic diet contained about 3000 kcal. Included in the diet were meat, cereal, and dairy products, which were reconstituted before eating with water produced in the regeneration system. The weight of the daily packaged food ration for each man was 720 g. To satisfy the needs of the researchers for "fresh" vitamins, salad greens were cultivated during the experiment in the space greenhouse model: Khibin cabbage, cress, borage and dill. High-intensity lights were used in the greenhouse, simulating the solar spectrum. A special ion-exchange resin was used as a substrate. It was preliminarily saturated with nutrients. The growing area in the greenhouse was 7.5 m^2, illumination was 45 - 50 W/m^2 at the surface level of the substrate.

Sources of drinking water for the researchers were the urine they excreted and moisture from respiration and perspiration, condensed in the heat exchanger.

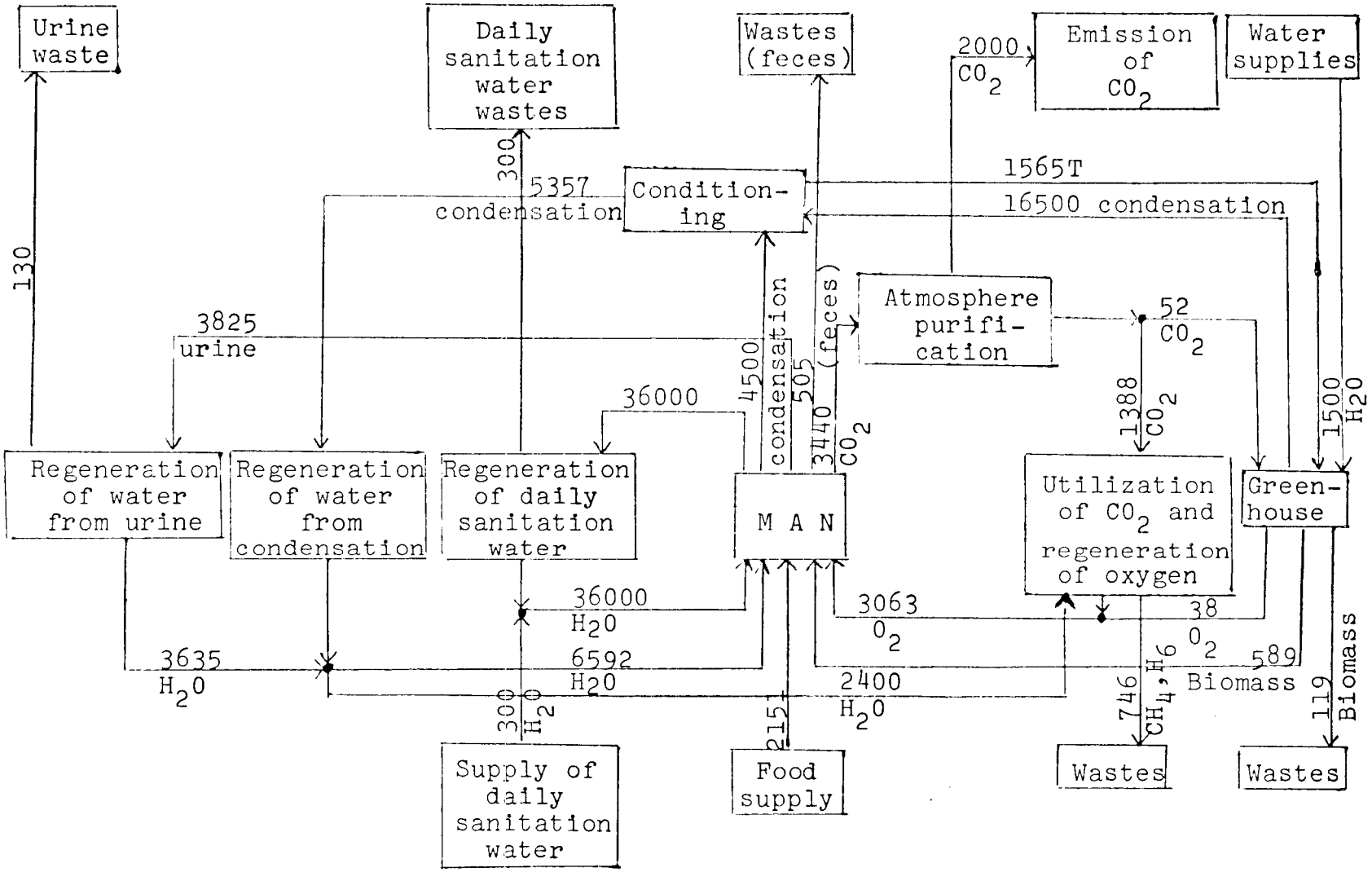

Figure 9. Schematic diagram of partially-closed matter cycle in year-long medical-technical experiment.

Drinking water was regenerated from urine by oxidation-catalytic methods in several stages: filtration of the urine; evaporation; high-temperature oxidation of organic compounds to elementary gases and oxides with the aid of a catalyst; condensation. After the condensate was enriched with the proper salts and microelements, it was used as drinking water [9]. /50

As about 600* g of water was contained in the daily amount of urine and 1500 g was consumed, the deficit of drinking water in the amount of 900 g/day was made up by a regeneration unit condensed atmospheric moisture. Water was regenerated from the condensate by oxidation-sorption methods which included filtration, oxidation of organic compounds under the effect of ultraviolet light, additional purification in ion-exchange resins and enrichment of the resultant water with salts and microelements [8].

Daily sanitation water was used for toilet, shower and sink. So-called kitchen water, left after washing dishes, was regenerated by oxidation-catalytic methods, similar to those used in regenerating water from urine. The rest of the daily sanitation water was regenerated by the coagulation method.

Oxygen was produced in a regeneration system composed of two units: an electrolysis unit and a unit utilizing carbon dioxide. After being purified of alkali aerosol, it entered the living compartment and the hydrogen entered the unit utilizing carbon dioxide [20]. In the utilization unit, water was produced by catalytic hydrogenation of the carbon dioxide discharged by the researchers. Methane produced in the reaction was not regenerated and was jettisoned.

*Translator's Note: The foreign mistakenly gives 1600 grams.

The air in the sealed cabin was cleared of carbon dioxide, and its concentration was controlled by an atmosphere purification system composed of three units: a unit for drying the air using regenerative synthetic zeolites* and a unit concentrating carbon dioxide with the use of these same zeolites. /51

Thermo-vacuum methods were used to regenerate zeolites in the absorption and concentration units. After being purified, the air was again humidified and returned to the living compartment, and the concentrated carbon dioxide was directed into the utilization unit.

Special catalytic furnaces and bactericidal filters were included in the atmosphere purification system to cleanse the air of toxic gases (organic substances, amino-compounds, carbon monoxide, hydrogen sulfide, etc.) and microbic flora. Solid human wastes were not included in regeneration and utilization processes.

Auxiliary systems for providing oxygen and eliminating carbon dioxide in the experiment were provided by regeneration unit with oxygen-containing compounds and an autonomous unit with chemical absorbents of carbon dioxide.

During the experiment the researchers lived in a sealed cabin, consisting of a living compartment and the experimental greenhouse, connected with each other.

The work and rest regime of the researchers was based on the combined duties performed by the researchers (24-hour shifts were only introduced during simulated emergency situations,

*Translator's Note: This is a hydrated double silicate; probably the active constituent in permutit.

which will be discussed later).

According to the research program, twice during the year-long experiment, in the eighth and the eleventh months, emergency situations were simulated by artificial deviation of individual life-support systems or by shifting them to a different work regime.

When emergency conditions were being simulated, oxygen concentration was decreased to 16 - 17%, and carbon dioxide concentration increased to 1 - 3%. Temperature in the living compartments was maintained at 28 - 30° C and humidity increased to 15 - 18 g/m^3. Water consumption quotas were decreased: drinking water to 1.2 kg/man per day, daily sanitation water to 4.0 kg/hr per day. Calories in the diet were decreased to 2500 kcal. The work and rest regime of the researchers during this period was regulated by a special chart calling for 24-hour shifts. /52

The simulated emergency situations, putting an additional load on the basic human physiological systems, helped to expose latent processes in the organism and to evaluate its reserve potentialities. Analysis of data obtained during simulated emergency situations showed that the researchers satisfactorily withstood the severe conditions in the living compartments and that the life-support systems operating during this period kept the air within given parameters (Figure 10) and maintained efficiency until the end of the experiment.

The testing showed that properly calculated amounts of reserve elements and well worked out methods of replacing and rechecking the elements make complete operational recovery of the unit possible without essential loss to the program.

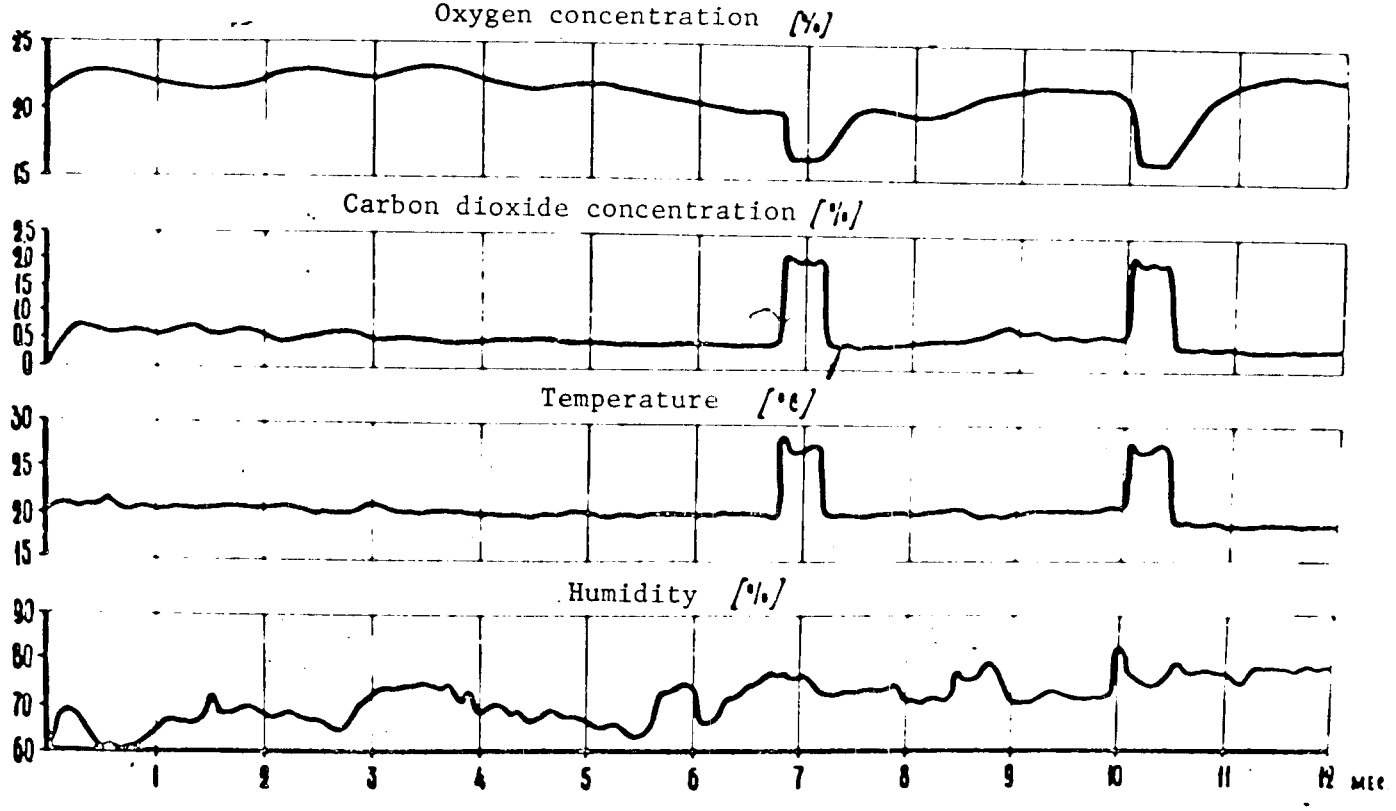

Figure 10. Change in parameters of the microclimate in the living compartment during year-long medical-technical experiment.

During the experiment, an interesting feature of the effect of the life-support system's work regime on human reliability (resistance) was revealed. It was shown that the most rational work regime (in terms of system reliability) maintained within given narrow limits is unsatisfactory with respect to maintaining high human resistance to the effect of experimental space /54
flight factors. This was especially pronounced in the simulation of possible emergency situations when preliminary "build up" of the basic parameters of environmental air in a wide range greatly increased the resistance and conditioning of the organism to the effect of unfavorable conditions in an emergency situation (high humidity and temperature). The reliability of the work of each link in the life-support system depends, in many respects, on considering the interrelations of links, not only during testing, but also during operation. Refinement of any one link without considering its place in the system could lead to reduced effectiveness of adjacent links. For example, creating more effective detergents in some cases involves adding ethanol or alkali to their composition. As a result of evaporation in use, some of these substances become part of the condensate of atmospheric moisture, which can also cause breakdowns in the unit regenerating water from the condensate.

Studies of mass-exchange processes during the experiment have contributed a great deal to medical-biological and technical-engineering research.

This is illustrated by the two examples considered below: (a) continuous data on oxygen consumption and carbon dioxide liberation for a prolonged period of time supplement physiological research on the functions of external respiration, and (b) data on drinking water consumption and urine excretion can supplement the study of water exchange.

a) Data Analysis of Carbon Dioxide Discharge and Oxygen Consumption /55

In the course of analyzing the data, information about changes in the following values was used:

— partial pressure of carbon dioxide, oxygen and water vapors in the sealed cabin; the latter is calculated according to relative humidity and air temperature;

— absolute pressure in the sealed cabin;

— oxygen entering the sealed cabin from the oxygen control system and carbon dioxide appearing in the sealed cabin as a result of "leaks" in the atmosphere purification system. According to data on changes in these values over a long period of time (about 30 days), rates of oxygen consumption and carbon dioxide discharge by the crew are calculated for the step of the experiment being analyzed. Subsequent statistical analysis of the functions under examination determined:

1. Mathematical expectation and standard deviation as a function of time of day.

2. Autocorrelation function up to long time shifts (several days).

A similar analysis was made for time intervals pertaining to various steps of the experiment at different lengths of time from the beginning of the experiment.

Figures 11 and 12 give examples of several results. Figure 11 shows the mathematical expectation M(t) and the mean square

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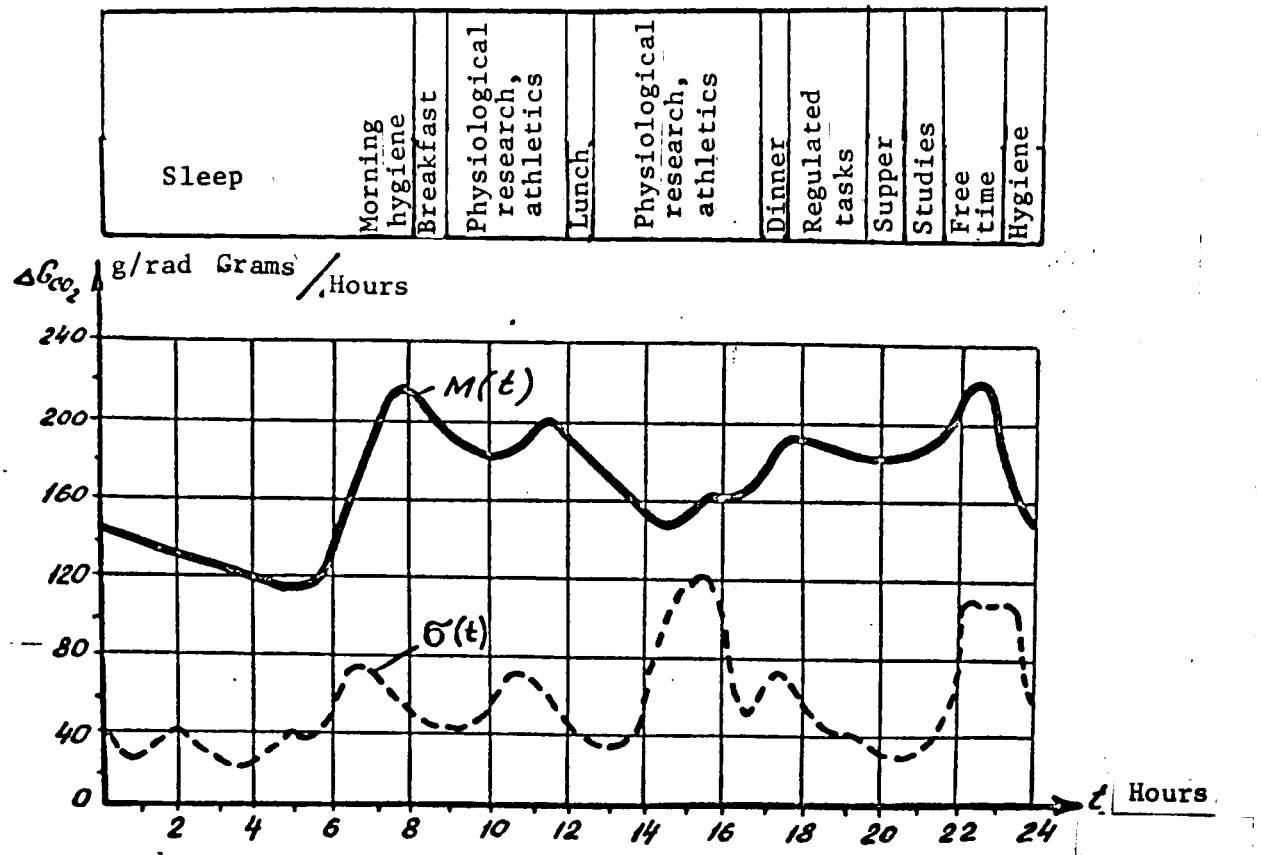

Figure 11. Discharge of carbon dioxide.

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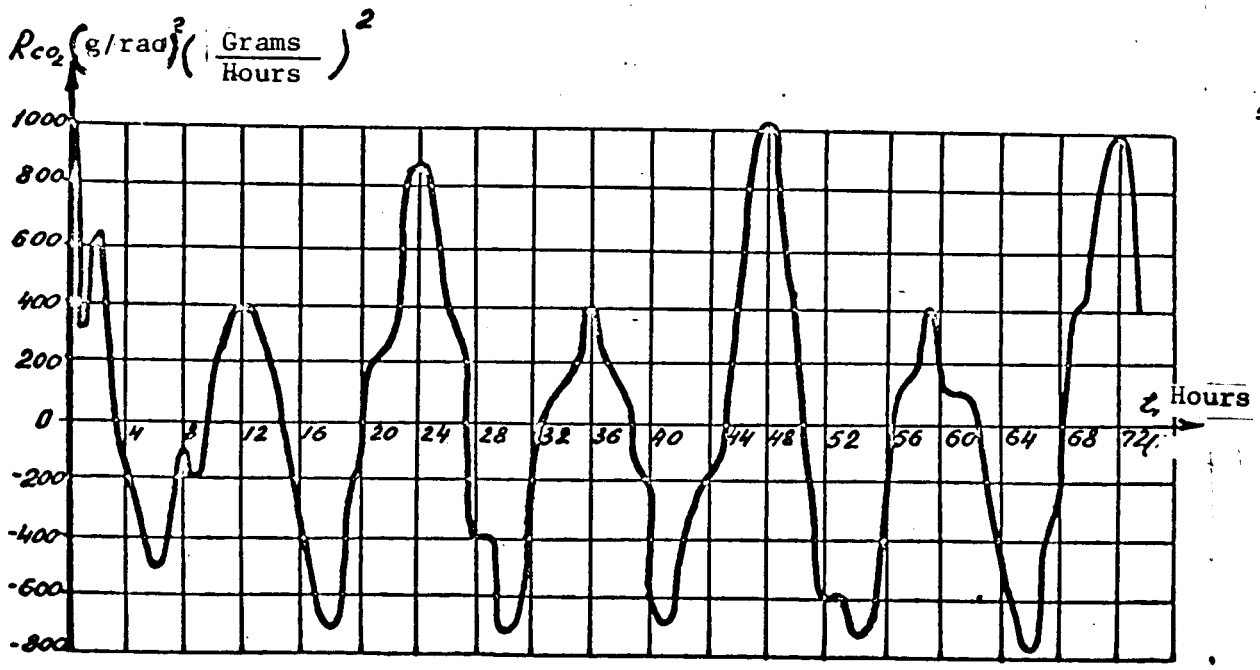

Figure 12. Autocorrelation function of carbon dioxide discharge rate.

deviation $\sigma(t)$ for the rate of carbon dioxide discharge. Characteristic aspects of these functions are: reduced activity during the sleep period (0 - 0700) and during the daytime rest period (1400 - 1500), and increased activity during the morning hours and before sleep. Also typical are increased random deviations (function peaks) in periods when activity levels are changing — upon awakening (about 0700), in the transition from daytime rest to work (1500 - 1600), and before and after the activity peak before sleep (2200 - 2400). One reason for increased random deviations might be slight variations in a given work and rest regime. /58

A typical feature of the autocorrelation function shown in Figure 12 is its periodicity for large time shifts. This is revealed by comparing the ordinates of the autocorrelation function in the interval between 24 hours and 48 hours with analogous ordinates in the interval between 48 and 72 hours. This clearly indicates periodic components in the rate of carbon dioxide discharge.

If the carbon dioxide discharge rate is considered to be a combination of two components:

— the first component is determined, and is established by the given activity regime of the crew;

— the second component (deviation) is an ergodic random function, fixed for the interval of time being analyzed, independent of the determined component; then the statistical characteristics of random variations can be determined (the autocorrelation function and, therefore, dispersion and spectrum).

b) Analysis of Data on Water Consumption and Urine Excretion

The initial statistical analysis of the data was made when the statistical moments to the fourth order, inclusively, were determined (mathematical expectation, dispersion, assymetry and excess), and the hypothesis about normal and logarithmic-normal distribution laws was verified. Total data for the entire crew and individual data for each participant in the experiment are analyzed, with and without consideration of the time of simulated emergency situations. Some results are given in Table 3. /59

TABLE 3. SOME STATISTICAL DATA ON WATER EXCHANGE

Name	Indices	Water consumption g/day		Urine excretion g/day	
		m.e.	m.s.d	m.e.	m.s.d
Bozhko		2440	280	1690	380
Manovtsev		2160	230	1540	310
Ulybyshev		2150	180	1500	290

The table gives the mathematical expectation (m.e.) and mean square deviation (m.s.d.) for individual water consumption. A characteristic aspect is the increased water consumption and urine excretion of Bozhko with a simultaneous increase in random deviations from average.

Another aspect of the analysis was screening of the random deviations to reveal the effect of various conditions of the experiment and its duration on changes in urine excretion and

water consumption by evaluating regular changes in the functions analyzed. It is necessary to process the data to solve the filtration problem, where unknown changes appear as the effective signal.

The filtration was based on assumptions with regard to the signal being analyzed: /60

(a) the signal is stationary;

(b) it consists of an unknown average value, of non-correlating random deviations from the average, and "noise";

(c) the random components resemble "white noise".

An analysis of the experimental data established that:

(1) for all analyzed functions, there are similar values for the order of the effective signal smoothness and the power of the optimal filter polynomial (they are 1 and 4, respectively). This indicates identical properties of the analyzed functions, which is explained by the significant effect of experimental conditions, which were the same for all participants;

(2) the filtered values of the analyzed functions were determined (examples given in Figures 13 and 14). Water consumption (Figure 13) decreased toward the middle of the experiment, and then increased again; brief peaks were also typical. Marked decreases in the discharge of excreted urine during simulated emergency situations are significant (about 200 and 300 days from the start of the experiment). An increase is observed during holiday diets (for example, about the 50^{th} day from the start of the experiment — New Year's Eve); introducing biomasses from

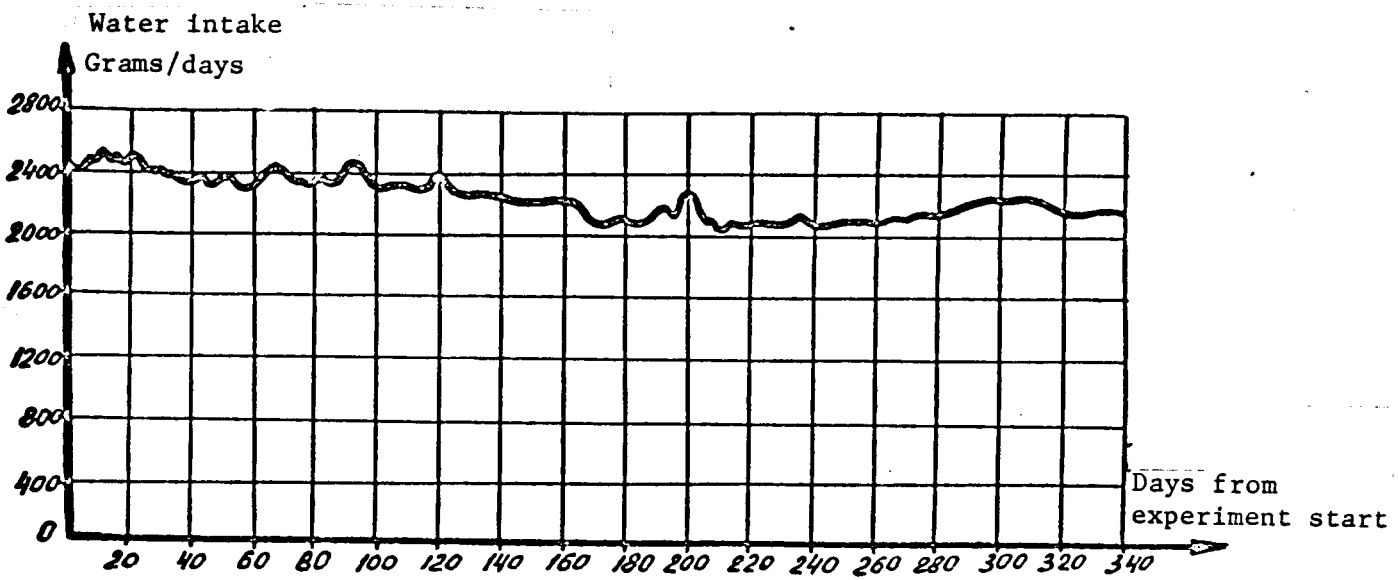

Figure 13. Average water consumption during the experiment.

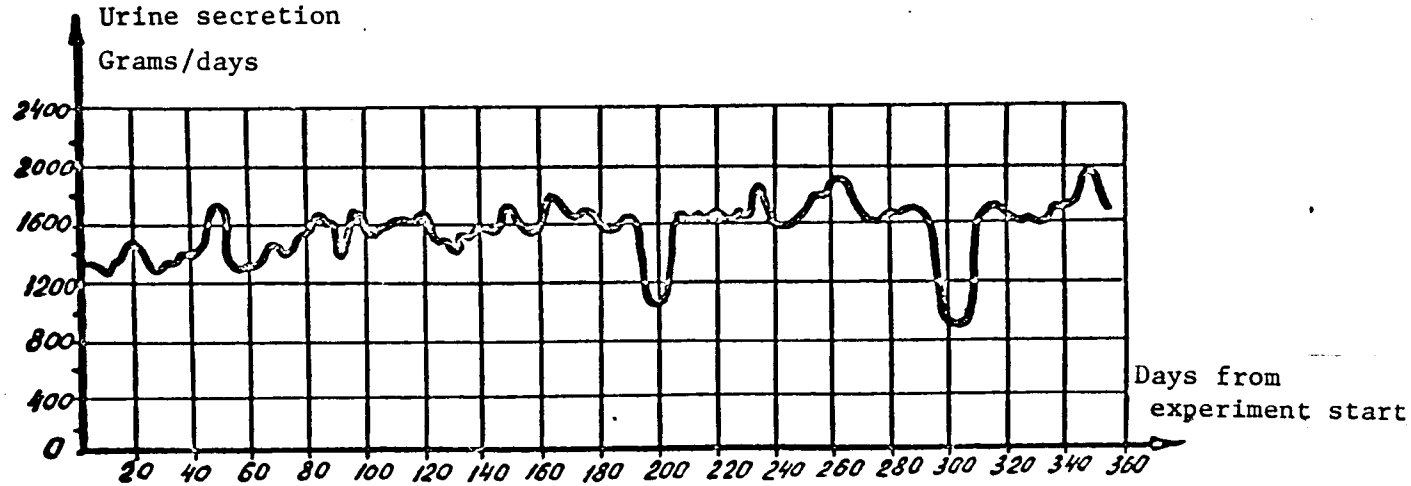

Figure 14. Average amount of excreted urine.

the vitaminic greenhouse into the diet (beginning with the 70th day, lasting until the end of the experiment) caused steady increased diuresis until completion of the experiment.

(3) autocorrelation functions were established for random deviations from the signal given at the optimal filter outlet. This could be used to judge individual characteristics in random deviations and the effect of experimental conditions on the deviations. /63

Figure 15 in particular shows the standardized autocorrelation function $\rho(\tau)$ for random deviations in water consumption. Peaks near 5, 10, 15th day time shifts indicate a correlation between water-consumption and five-day intervals. The only factor in the experimental conditions which could be responsible for five-day periodicity is the five-day change in diet. Therefore the mathematically analyzed data given in Figure 15 indicate the effect of diet change on water consumption.

It is not possible within the limits of this report to consider other examples of the agreement between experimental data used as starting points for theoretical research. However, the examples cited are quite typical in evaluating and reviewing our preliminary ideas about mass-exchange characteristics of the LSS and of man as an important element in the system.

Data from the year-long experiment substantiated the working hypotheses and estimates of the daily oxygen consumption and carbon dioxide discharge, as well as estimated average water consumption and urine discharge. Therefore, we have sufficiently valid reference data for the further development of theoretical structures. On the basis of these data, we can proceed with studies involving optimization of the system and selection of algorithms.

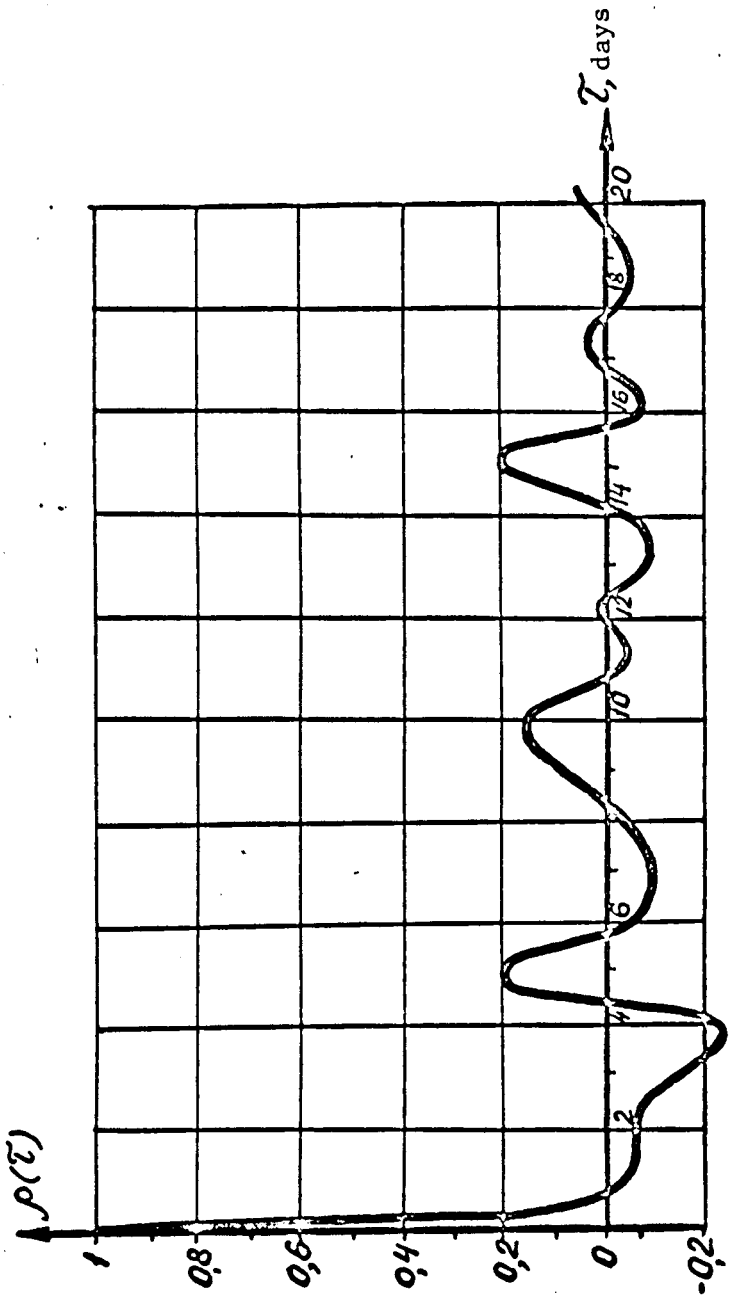

Figure 15. Standardized autocorrelation function for ΔX.
Average water consumption for three researchers.

Theoretical and experimental studies of mass-exchange processes in the life-support system used in the year-long medical-technical experiment have verified the productivity of the selected directions of research. The information obtained by analyzing experimental data makes possible more accurate theoretical studies of the system and is the basis of loading requirements for links in the life-support system, which process metabolism products and provide regenerated substances needed by the crew. /65

It must be noted that the principle of a sequential, staged connection of individual systems in the complex, which was used in the experiment, was completely justified. On one hand, it led to a more qualitative evaluation of the role and characteristics of each system in the complex, and it was possible to note certain changes in parameters of the environmental medium developing after the corresponding systems were in operation. On the other hand, it made possible a biological-technical evaluation of individual combinations of systems characterized by different regeneration coefficients. It was also possible to establish the most important connections between material and information flows.

Careful interpretation and thorough analysis of clinical-physiological and biological-technical information will make it possible in the future to compile a complete picture of the reactions of both individual physiological systems and the entire organism, which develop during prolonged human existence in a small sealed cabin under specific water and oxygen cycle conditions. It will also be possible to increase the resistance of the human organism to the effect of certain factors of prolonged space flight and to further refine technological life-support systems.

REFERENCES

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1. Agadzhaniyan, N. A., Yu. P. Bazin, G. P. Doronin, Ye. A. Il'in, A. G. Kuznetsov and N. I. Yezepchuk. The Effect on the Human Organism of Prolonged Existence in a Small Sealed Room. In the collection: "Problemy kosmicheskoy biologii" (Problems in Space Biology), Nauka Press, Vol. IV, 1965.

2. Adamovich, B. A., A. V. Kostetskiy, V. A. Kurochin and G. G. Ter-Minas'yan. Mathematical Modeling of Heat-Moisture Processes in Sealed Spacecraft Cabins. Kosmicheskaya biologiya i meditsina, Vol. 5, 1967, p. 25.

3. Adamovich, B. A. and Yu. G. Nefedov. Development of the Ideas of K. E. Tsiolkovskiy on Creating Life-Support Systems for Spacecraft, Trudy vtorykh chteniy, posvyashchennykh pazrabotke nauchnovo naslediya i razvitiyu idey K. Ye. Tsiolkovskovo (Works of the Second Lectures Devoted to Developing the Scientific Heritage and Ideas of K. E. Tsiolkovskiy), Moscow, 1968, p. 25.

4. Adamovich, B. A. and Yu. G. Nefedov. Bio-engineering Problems Related to Living in Spacecraft and Interplanetary Stations, "Rivista Med. Aeronaut.", Vol. 31, No. 1, 1968, p. 109.

5. Adamovich, B. A. and Yu. G. Nefedov. Biological-Technical Problems of Living in Spacecraft and Planetary Stations, Doklady na konferentsii OON po issledovaniyu i ispol' sovaniyu kosmicheskovo prostranstva v mirnykh tselyakh. (Report to the UN on the Study and Peaceful Uses of Outer Space), Vienna, 1968.

6. Adamovich, B. A. and G. G. Ter-Minas'yan. Problems in Creating Life-Support Systems in Spacecraft, Kosmicheskaya biologiya i meditsina, Vol. 1, 1967, p. 20.

7. Adamovich, B. A., Yu. G. Nefedov and S. B. Maksimov. Life-Support during the Year-Long Medical-Biological Experiment, Vestnik APN, 1968, p. 301.

8. Bollod, A. A., L. E. Yegorova, V. A. Mironov et al. A Study of Ways of Regenerating Water from Condensed Atmospheric Moisture Using the Sorption Method. In the collection: Trudy IF CO AN SSSR, 1966.

9. Bobe, L. S., B. G. Gusarov, V. M. Novikov et al. Regenerating Water from Moisture-Containing Human Wastes and a Biocomplex by the Oxidation-Catalytic Method. In the collection: "Problemy zamknutykh ekologicheskikh sistem" (Problems of Closed Ecological Systems), 1967.

10. Burnazyan, A. I., V. V. Parin, Yu. G. Nefedov, B. A. Adamovich et al. The Year-Long Medical-Technical Experiment in a Ground Life-Support System Complex, Kosmicheskaya biologiya i meditsina, 1969, p. 1.

11. Burnazyan, A. I., V. V. Parin, Yu. G. Nefedov and B. A. Adamovich. The Year-Long Medical-Technical Experiment Under Conditions of a Partially Closed Matter Cycle, "Aerospace Med.", Vol. 40, Oct, 1969, p. 10.

12. Volynkin, Yu. M. and P. P. Saksonov. Physical Conditions of Space Flight and Their Biological Characteristics. In the collection: "Problemy kosmicheskoy biologii" (Problems in Space Biology). Nauka Press, Vol. III, 1964, p. 10.

13. Vorodin, G., A. Polivoda and Ye. Vinogradov. Life-Support Systems for Spacecraft, "Aviatsiya i kosmonavtika", Vol. 9, 1966, p. 44.

14. Voronin, G. I. and A. I. Polivoda. Zhizneobespecheniye ekipazhey kosmicheskikh korabley (Life Support of Spacecraft Crews), Mashinostroyeniye Press, Moscow, 1967.

15. Genin, A. M. Principles of Formulating an Artificial Environment in Spacecraft Cabins. In the collection: "Problemy kosmicheskoy biologii" (Problems in Space Biology), "Nauka" Press, Vol. III, 1964, p. 59.

16. Gol'dshvend, B. L., V. G. Gusarov, A. G. Lobanov, Yu. Ye. Sinyak, A. P. Tereshchenko, S. V. Chizhov and V. M. Shilov. The Problem of Utilization Under Conditions of Prolonged Space Flight. In the collection: "Problemy kosmicheskoy biologii" (Problems of Space Biology), "Nauka" Press, Vol. III, 1964, p. 80.

17. Gol'dshvend, B. L., B. G. Gusarov, A. G. Lobanov et al. The Question of Developing a Physical-Chemical Utilization Link In Prolonged Spacecraft Flights. In the collection: "Problemy kosmicheskoy biologii" (Problems of Space Biology), Moscow, Nauka, Vol. III, 1964.

18. Gorbov, F. D. and M. A. Novikov. Experimental Psychological Studies of Groups of Cosmonauts. In the collection: "Problemy kosmicheskoy biologii" (Problems in Space Biology), "Nauka" Press, Vol. IV, 1965, p. 17.

19. Gorbov, F. D. and M. A. Novikov. Experimental Psychological Studies of Groups of Cosmonauts. In the collection: "Problemy kosmicheskoy biologii" (Problems of Space Biology), "Nauka" Press, Vol. IV, 1965, p. 17.

20. Grishayenkov, B. C., L. L. Zablotskiy, O. F. Ostapenko, Yu. M. Semenov and A. G. Fomin. Methods of Producing Oxygen by Electrolytic Dissociation of Water Under Weightless Conditions. In the collection: "Problemy kosmicheskoy biologii" (Problems in Space Biology), "Nauka" Press, Vol. III, 1964, p. 396.

21. Gazenko, O. G. Space Research and the Biological Sciences, Doklady no konferentsii OON po issledovaniyu i ispol' zovaniyu kosmicheskovo prostranstva v mirnykh tselyakh (Reports to the UN Conference on the Study and Peaceful Uses of Outer Space), Vienna, 1968.

22. Gurovskiy, N. N., M. D. Yemel'yanov and Ye. A. Karpov. Basic Principles of Special Training for Cosmonauts. In the collection: "Problemy kosmicheskoy biologii" (Problems of Space Biology), "Nauka" Press, Vol. IV, 1965, p. 10.

23. Denisov, V. G. Some Aspects of the Combination of Man and Machines in Complex Control Systems. In the collection: "Problemy kosmicheskoy biologii" (Problems in Space Biology), AN SSSR Press, Vol. II, 1962, p. 54.

24. Ivanov, D. I. and A. I. Khromushkin. Sistemy zhizneobespecheniya cheloveka pri vysotnykh i kosmicheskikh poletakh (Human Life-Support Systems in High-Altitude and Space Flights), Mashinostroyeniye Press, Moscow, 1968.

25. Kakurin, L. I. and Yu. N. Tokarev. K voprosu issledovaniya rabotosposobnosti kosmonavta v eksperimente primenitel'no k zadacham kosmicheskovo poleta (Study of Cosmonaut Efficiency in Experiments as Applied to Problems of Space Flight), "Nauka" Press, Vol. III, 1964, p. 226.

26. Korobkov, A. V. Physical Controls as a Means of Maintaining Stability of the Internal Environment of the Cosmonaut. In the collection: "Problemy kosmicheskoy

biologii" (Problems in Space Biology), AN SSSR Press, Vol. II, 1962, p. 68.

27. Kratkiy spravochnik po kosmicheskoy biologii i meditsine (Concise Handbook of Space Biology and Medicine), Meditsina Press, Moscow, 1967.

28. Lebedinskiy, A. V., S. A. Levinskiy and Yu. G. Nefedov. General Patterns of Human Reactions to the Complex Effect of Factors in a Medium Typical of Spacecraft Cabins. Materialy XV kongressa mezhdunarodnoy astronavticheskoy federatsii (Data from the XV International Astronautical Federation), Warsaw, Vol. IV, 1964, p. 77.

29. Lebedinskiy, A. V. and Yu. G. Nefedov. Problems of Radiation Danger in Space Flights. In the collection: "Problemy kosmicheskoy biologii" (Problems in Space Biology), AN SSSR Press, Vol. II, 1962, p. 11.

30. Levashov, V. V. New Aspects of Personal Hygiene. In the collection: "Problemy kosmicheskoy biologii" (Problems in Space Biology), "Nauka" Press, Vol. IV, 1965, p. 165.

31. Moiseyeva, A. A., Yu. S. Koloskova, Yu. Ye. Sinyak and S. V. Chizhov. Providing the Crew with Water During Space Flights. In the collection: "Problemy kosmicheskoy biologii" (Problems in Space Biology), Vol. VII, 1967.

32. Nefedov, Yu. G., B. A. Adamovich, A. S. Ushakov and S. V. Chizhov. Life in a Spacecraft and Planetary Station. Doklad na X mezhdunarodnom simposiume Kospar (Report to the X International Cospar Symposium), Amsterdam, 1968.

33. Nefedov, Yu. G. and B. A. Adamovich. Living and the Biological-Technical Aspects of Life-Support Systems in Spacecraft and Planetary Stations. Materialy XVII kongressa mezhdunarodnovo astronavticheskoy federatsii (Material from the XVII Congress of the International Astronautical Federation), Madrid, 1967, p. 205.

34. Nefedov, Yu. G. and B. A. Adamovich. Development of the Ideas of K. E. Tsiolkovskiy on Creating Life-Support Systems for Spacecraft. Doklad na konferentsii posvyashchennoy 110-letiyu so dnya rozhdeniya K. E. Tsiolkovskovo (Report to the Conference in Honor of the 110th Anniversary of the Birth of K. E. Tsiolkovskiy), Kaluga, 1967.

35. Olizarov, V. V. Sistemy obespecheniya zhiznedeyatel'nosti ekipazhey letatel'nykh apparatov (Life-support Systems for Aircraft Crews), Izdatel'stvo Voyenno-vozdushnoy inzhenernoy akademii im. N. Ye. Zhukovskiy, Moscow, 1962.

36. Sinyak, Yu. Ye. and S. V. Chizhov. Water Regeneration in the Spacecraft Cabin. In the collection: "Problemy kosmicheskoy biologii" (Problems in Space Biology), "Nauka" Press, Vol. III, 1964, p. 104.

37. Sinyak, Yu. Ye. and S. V. Chizhov. Water Regeneration in the Spacecraft Cabin. In the collection: "Problemy kosmicheskoy biologii" (Problems in Space Biology), Moscow, "Nauka" Press, Vol. III, 1964, p. 104.

38. Sinyak, Yu. Ye. and S. V. Chizhov. Water Regeneration in the Spacecraft Cabin. Problemy kosmicheskoy biologii (Problems in Space Biology), "Nauka" Press, Vol. III, 1964.

39. Sisakyan, N. M., V. V. Parin, V. N. Chernigovskiy and V. I. Yazdovskiy. Some Problems in the Study and Conquest of Outer Space. In the collection: "Problemy kosmicheskoy biologii" (Problems in Space Biology), AN SSSR Press, Vol. I, 1962, p. 5.

40. Tsiolkovskiy, K. E. Izbrannyye trudy (Collected works), AN SSSR Press, 1962, p. 197.

41. Tsiolkovskiy, K. E. Zhizn' v mezhzvezdnoy srede (Life in the Interplanetary Medium), "Nauka" Press, 1964, pages 50, 61, 64, 75.

42. Tsiolkovskiy, K. E. Issledovaniye mirovykh prostranstv reaktivnymi priborami. Izbrannyye trudy K. E. Tsiolkovskogo (Using Rocket Devices to Study Outer Space. Collected Works of K. E. Tsiolkovskiy), AN SSSR Press, 1962, pages 196, 197, 199.

43. Chizhov, S. B., Yu. Ye. Sinyak, V. V. Krasnoshchekov, B. G. Gusarov, S. O. Kuznetsov, I. V. Aleksandrova and G. V. Ilgach. Study of the Oxidation-Catalytic Method of Mineralizing Wastes in a Matter-Cycle System. "Kosmicheskaya biologiya i meditsina", Vol. 2, 1968, p. 6.

44. Shepelev, Ye. Ya. Some Problems of Human Ecology in Closed Matter-Cycle Systems. In the collection: "Problemy kosmicheskoy biologii" (Problems in Space Biology), "Nauka" Press, Vol. IV, 1965, p. 169.

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